STATUS REPORT OF IHRA COMPATIBILITY AND FRONTAL IMPACT WORKING GROUP

Peter O'Reilly
DfT (United Kingdom) Chairman of IHRA Vehicle Compatibility and Frontal Impact Working Group on behalf of the Group
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ABSTRACT

The work of this International Harmonised Research Activity (IHRA) group has continued to focus on compatibility research with the prime aim of improving occupant protection in cars by developing internationally agreed test procedures designed to improve the compatibility of structures in front to front, and front to side, impact.

Compatibility is a complex issue but offers an important step towards the better protection of car occupants. To date the group has focussed on frontal performance tests although benefits need not be confined to frontal impact. Group members continue to work actively in research programmes to enhance understanding and develop potential test procedures to assess compatibility.

A number of potential test procedures remain open in the longer tem. But, in recent meetings, effort has concentrated on defining key aspects and assessment criteria for a potential phase 1 test as a first step to improve vehicle compatibility. There is a significant degree of common thinking and purpose and, although issues and challenges remain, a phase 1 step should be possible.

INTRODUCTION

It has been recognised for many years that the protection of vehicle occupants is influenced, not only by the characteristics of the vehicle they are travelling in, but also by the characteristics of the vehicle with which it collides. Historically, the emphasis was on mass alone being dominant. But now structural interaction, passenger compartment strength and frontal force are seen as key compatibility factors.

Up to 2001, there were separate IHRA groups for frontal impact and compatibility. In 2001, the IHRA Frontal Group suggested a first step towards frontal impact harmonisation based on using both existing frontal full width and offset impact tests. Future activity in both frontal impact and compatibility areas was combined within one IHRA group from ESV 2001. (The European Union and the European Enhanced Vehicle-safety Committee (EEVC) has continued to provide the chairman.)

AIMS OF THE GROUP AND BROAD APPROACH

The prime aim of the compatibility work is to develop internationally agreed test procedures designed to improve the compatibility of car structures in front to front and front to side impact, thus improving the level of occupant protection provided in these impacts. A secondary consideration for compatibility is to bear in mind any implications for protection in impacts with pedestrians, heavy goods vehicles and other obstacles. The prime focus up to now has been on front to front impacts (car to car including LTV/SUVs).

Research will continue on improved understanding of side impact compatibility to define the possibility for a side impact test procedure or, at least, to ensure that any front test procedure helps or does not disadvantage side impact protection. Similarly, research will continue to help ensure that steps to improve compatibility help or do not disadvantage frontal impact self-protection.

Car-to-car and car-to-LTV/SUV crashes have been the main area of work, with LTV crashes the dominant concern in North America. Recently the group has concentrated on the development of a potential Phase 1 test procedure and assessment criteria aimed at improving frontal structural interaction. Initially this would mainly influence LTVs but could also influence car design. The addition of further metrics or test procedures in later phases should ideally allow the evaluation of further compatibility aspects i.e. frontal force levels and compartment strength. Vehicles of interest in the different regions represented by members were covered in the last ESV report.

Potential users of any test procedures could vary widely and range from manufacturers wishing to evaluate the compatibility of their products to regulators. The judgements and the administrative process in considering the suitability of any proposed test(s) as a potential basis for regulation would be individual to each region.

This paper seeks to distil the position of the group and, while it draws on the research of members, it does not attempt to summarise the range of data which individual members have presented. The work of members and their associated organisations appears in individual reports and publications including ESV papers.

INTERNATIONAL CO-OPERATION

Membership, Participation And Meetings

Members represent governments in Europe, USA, Australia, Canada and Japan and industry members are nominated by industry in Japan, Europe and USA. In addition individual experts have sometimes attended meetings, particularly when from the host country or group.

Opportunities are sought to have common technical sessions with EEVC compatibility (WG15) meetings. Informal links with the IHRA Side Impact group continue through some common membership and a joint meeting with this group was held after ESV 2003.

Recent Meetings

Since the last ESV, there have been 7 meetings.
19th meeting 27-28 May 2003 (27 May jointly with IHRA Side Impact Working Group) Tokyo Japan
20th meeting 17-18 September 2003 (17 September jointly with EEVC WG15) Paris France
21st meeting 20-22 January 2004 (jointly with EEVC WG15) Gothenburg Sweden
22nd meeting 13-14 May 2004 (open to wider US attendance) Washington USA
23rd meeting 13-15 September 2004 London England
24th meeting 14-16 December 2004 Paris France
25th meeting 14-15 February 2005 London England

There continues to be an open flow of information on findings between members with normally at least a day spent on presentations of the latest research. Three joint meetings have been held, two with EEVC WG15 and one with the IHRA Side Impact WG. There has been a partial move towards three day meetings, as used when joint meetings are held with the EEVC. This gives more time for presentations and discussions and also offers the prospect of fewer meetings overall. Unusually there were 4 meetings in 2004, mainly linked to the effort towards a phase 1 test outline. EEVC/European industry workshops were open to members of the group if able to attend. This included one on 23/24 February 2005 on VC-COMPAT results and industry work.

Co-operation Within Regions

Aside from the links through IHRA, there is a significant amount of co-operation within and between the regional organisations involved in IHRA. Some direct links are outlined below.

EEVC and European industry – Links through industry representation in working groups and industry co-operation with VC-COMPAT
Individual EEVC members – co-operation with Renault, PSA Peugeot Citroen, VW, Ford and others
NHTSA – co-operation with Ford, Australia, Canada, Europe, MIRA, Cellbond, TRL, Japan, Honda and VW
Australia – co-operation with Subaru, Ford, Renault, NHTSA
Japan – co-operation with JAMA, NHTSA, Australia, UTAC.

Reviews Of Data

Structural Survey: Links continued following earlier structural survey work. Japan had led on this work topic and continued to report to the group both on results and, in addition, those aspects where it had identified differences or inconsistencies between different teams, when using the same VC-COMPAT protocol. Large lateral differences were seen for engine/gearbox data and Japanese measurements of one vehicle were up to 133 mm different to the European data. To resolve this issue, the measurement protocol was revised by UTAC in co-operation with Japan. Points made included determining a reference plane to remove any effects due to suspension ride height differences, investigating point differences and listing the high priority measurements. Liaison on this was mainly direct between the groups involved. It was felt that any issues were worth resolving. NHTSA which has work in this area also wanted to use the most consistent protocol so that results in databases could be used with high reliability in future analyses.

Accident Review: Canada presented work on its review of research related to published analyses of accident data, essentially North American sources, including some estimates related to potential casualty benefits. Members were asked to provide accident data related to front, side, belted, unbelted and vehicle class and, if possible, others eg gender and age group to allow further work on its review.

Vehicle types now range from minicar, mini truck, car, small LTV, one box vehicles, small truck and truck and there has been further clarification on accident classes. This work should progress further in 2005. Some regions have submitted statistics although Europe has encountered difficulties in obtaining the desired data. Preliminary analysis of data provided by Japan shows that, in frontal two vehicle crashes, car and minicar fatalities dominate the fatality totals, a high proportion being in car to truck collisions with car to car featuring less strongly. For minicar fatalities, the truck and car are both dominant. For two vehicle side impact, the car and minicar fatalities are dominant with truck and car followed by one box (MPVs and minivans) being the dominant striking vehicles.

Outline Of Members' Research Programmes

Members are actively involved in compatibility research programmes, often with cross-links. The emphasis in programmes tends to reflect regional fleets; for example, the focus is on LTV to car impacts in the USA and on car to car impacts in Europe.

Canada has led on a partially completed review of accident data. In addition, it has reported on some of its side impact work.

European industry work has included studies on reliably detecting the strength of crossbeams, repeatability/reproducibility of test procedures, some modelling work and development work on a deformation based metric. Industry is also contributing resources and some work towards the VC-COMPAT programme.

VC-COMPAT, the European programme on compatibility, has the objective of developing a suite of test procedures to assess and control car structures to improve frontal compatibility and is due to report in 2006. EEVC WG15, which has a steering role in VC-COMPAT, is to make recommendations on frontal impact compatibility test procedures in November 2006. The programme has separate car and truck elements. The car element has four packages (leaders in brackets); structural analysis (UTAC), cost benefit analysis (BASt), crash testing (TRL) both car to barrier and car to car, modelling (TNO) including developing an FE model of one of the barriers and the continued development of a fleet model. The truck element has included several car to truck baseline tests with existing European truck under-run guards (energy absorbing and rigid). In addition some member states have carried out extra research which supports the work of EEVC WG15.

A new one year European project (IMPROVER) covers diverse topics, one of which deals with SUVs. This element is led by TNO and the aim is to report on the potential effect of an increasing SUV population on safety.

US industry gave general information on some of the US activity aimed at a voluntary approach, including frontal impact compatibility subgroups investigating full width test procedures, possible LTV to car testing (short term) and the use of an MDB (longer term), and a possible supplementary test for secondary energy absorbing structure (SEAS). In addition some findings were presented from car to LTV tests.

NHTSA has reported on LTV to car (mid sized) full frontal and 50% offset tests plus side impact tests with the car as the target vehicle. The LTVs were chosen to reflect different characteristics such as AHOF and initial stiffness. In addition NHTSA have explored vehicle compatibility using a full width test, both with a rigid wall and a deformable element. Limited repeatability work has included a comparison of two car to car tests. Work continues on constructing and validating FE models for the study of car and LTV interaction and to support MADYMO models intended for fleet optimisation. In addition, a load cell wall (LCW) specification has been prepared.

The US car to LTV research by NHTSA and industry is based on the struck car in a full frontal impact experiencing a delta v comparable to that in barrier tests i.e. equal to 56 km/h in a full width test. The same LTV speed is used in the LTV to car overlap tests. In contrast, European car to car (overlap) tests are carried out with each vehicle at a constant speed (56 km/h) but, being car based, they are much closer in mass than the vehicles examined in the US work.

Japan has carried out a series of tests using a full width barrier, both rigid and with a deformable element, using different vehicles (mini, small and medium cars, MPV and SUV). Vehicle to vehicle full frontal tests were carried out for comparison. In addition Japan has carried out analyses related to potential metrics. Other work has included the analysis of various approaches to determine compartment strength based on the interpretation of force levels in an existing offset test.

Australia has reported on an analysis, using the results of earlier Australian PDB tests, to explore whether compartment strength could be reliably determined from the force level at rebound. More work is planned in this general area. Further car to car and car to PDB tests have also been carried out.

PHASE 1 PROPOSAL – POTENTIAL FIRST STEP

In 2004, group effort has been much more sharply focussed on a first step (Phase 1) proposal. This does not change the group's view on longer-term tests. All options remain open for future phases and the longer-term position is covered in a later section (Phase 2).

Introduction To Short Term Proposal

At the January 2004 meeting, it was agreed that the immediate focus of the group should be supporting the development of a compatibility test procedure that could be implemented in the short term. This step was discussed against a backdrop of the continued need to address LTVs which were the primary and pressing issue for North American members and markets. This is not the situation for all members; for example the EEVC prime interest is car to car compatibility.

benefits in taking advantage of this by ensuring the presence of LTV structures in this zone. An improvement in LTVs would offer the greatest chance of increasing structural interaction in impacts with both current and earlier car models which would be present in the fleet for many years to come. If possible, benefits should also be considered for car to car impacts. The heights of lower rails for vehicles of various classes (cars, MPV, 4WD, LCV) from the European VC-COMPAT structural survey are shown in Figure 1.

The work of the group has remained focussed towards a phase 1 test procedure and addressing in detail associated issues. There has been agreement on defining many of the full width barrier and load cell characteristics, partial evaluation of new metrics, repeatability plus further work on aspects and elements of the proposal.

The structures which a Phase 1 step would encourage on LTVs or cars were felt by industry members to be consistent with possible future vehicle designs if additional improvements in compatibility were introduced.

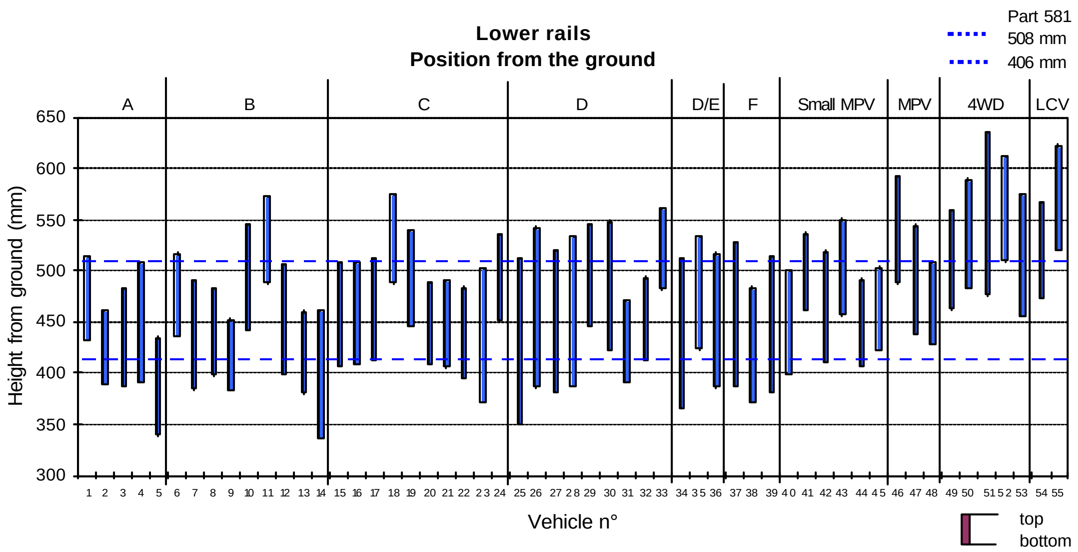

Figure 1. Height of lower rails for various vehicle classes in Europe (Source VC-COMPAT)

An element in subsequent discussion was a view that the vast majority of cars currently generate interaction forces in a similar area, given that most have a cross beam to meet bumper low speed impact standards such as 581. Therefore there should be

Summary Of Proposed Test For IHRA Phase 1

In December 2004, the group agreed that, in principle, the outline test procedure described below offers the best way forward for a phase 1 test with a focus on LTVs. The metrics are recent so they are only partially evaluated and not by all members. This agreement will be reviewed following further investigation of the proposal by group members, including the degree to which it affects the fleet. This applies to the initial step represented by phase 1a. The group hopes to add additional phase 1 requirements in 2005 to further improve compatibility.

Aims: The proposal aims

(a) To improve structural interaction primarily for LTV to car compatibility. One aspect would address crossbeam strength which could also benefit car to car compatibility.

(b) To minimise the number of tests by adapting the existing full width test by adding a LCW and deformable element while retaining its original function as a self-protection test.

Scope: The suggested scope is cars and LTVs (less than 10,000 lbs. gross).

Test Configuration: The proposal is a full width test carried out at 56 km/h into a wall equipped with an array of high resolution load cells and a deformable barrier face.

Load Cell Wall (LCW) Characteristics: There has been agreement on the definition of many of the characteristics of the full width LCW.

- Height and Width: The LCW should be flat and its height and width sufficient to cover full width and height of all vehicles to be tested.
- Individual Load Cell Size: 125 by 125 mm over full wall or subdivisions that can be summed to give 125 by 125 mm units.
- Vertical Position of LCW (on barrier): The group has agreed to use 80 mm ground clearance, the intention being to give a load cell boundary in the centre of the US 581 bumper area.
- A detailed LCW specification with acceptance criteria is being developed. (NHTSA with a few inputs from others.)

Deformable Face: A deformable face should cover all of the LCW. The deformable face proposed consists of two layers, each 150 mm deep, front layer 0.34 MPa crush strength and the rear layer 1.71 MPa crush strength, segmented to match the load cells.

Acceptance Criteria (Metrics) Phase 1a: The phase 1a vertical and horizontal metrics are intended to encourage sufficiently strong structure in a common interaction zone. In the vertical metric, target minimum load(s) would be set for (horizontal) rows in the common interaction zone and the metric would address loads lower than this value. The horizontal metric would involve target cell load(s) for cells within a row, based on the total row load. For those cells between the longitudinal rails, the metric would address load values that have lower values than the target cell load(s).

Phase 1a metrics would be based on LCW force measurements and are set out below.

- Vertical: A common interaction zone is defined vertically as 330-580 mm high, essentially the third and fourth load cell rows. For each row, a minimum row load of [100 kN] is proposed.
- Horizontal: The same two rows are examined. A target load would be derived related to the overall load in each row and, based on this, an assessment would be made on the load(s) in the inner cells, likely for [80%] of the vehicle width. A performance limit is to be proposed for this assessment.
- AHOF: NHTSA has shown a correlation between this metric and casualty risk in the existing US fleet. However AHOF alone is not felt to be sufficient, in particular for vehicles with SEAS. A limit would have to be proposed.

Discussion On Some Test Aspects And Choices

This section discusses some aspects of phase 1a, in some cases giving some background or explanation on the choices made.

Vertical Position of LCW on the Barrier: This takes advantage of the degree to which structure is present in this zone for cars. Positioning the ground clearance of the LCW to split the part 581 zone was preferred as this should maximise the sensitivity of a force measurement based approach for movement of relevant structures within this region. A ground clearance of 80 mm, combined with the 125 mm load cell spacing, results in the boundary between rows 3 and 4 being in the center of the 581 zone. Setting metrics for forces in the rows above and below this row boundary can then provide the desired influence.

The ground clearance of individual LCWs in service has varied; the range typically included 50 , 80, 125 and 165 mm, excluding those barriers where the first (lowest) row starts appreciably higher e.g. 250 mm. Some barriers which lend themselves readily to adjustment have changed to this ground clearance for new testing.

Deformable Face on Barrier: The deformable face was originally proposed by the EEVC as an improvement over a rigid wall for compatibility evaluation e.g. limiting engine inertial loads so that structural behaviour can be "seen" more clearly while minimising the effect on compartment deceleration pulse; a minimal effect is desirable, given that it is based on a self-protection test. Factors relevant to phase 1 include aiding the detection of SEAS and crossbeam structure which relate to the vertical and horizontal metrics proposed. For example, in recent tests, it detected the presence of SEASs 315 mm and 370 mm rearward of the front rail. There is not a precise distance which the barrier will reach into a vehicle; this will depend on the barrier and the degree and manner of deformation of the main structure (PEAS) before the SEAS becomes involved.

Canada, US, Europe and Australia support the deformable element with emphasis on various factors. For Japan the deformable barrier is an open question. Japan recognises that AHOF can be measured with a rigid barrier, but for extra compatibility information, a deformable element is needed. It has noted some examples of differences between rigid and deformable barriers in the deceleration pulse and structural deformation behaviour in its test program. Different perspectives can be held on whether any differences in these areas, e.g. in early pulse shape, airbag triggering and how structure is loaded, should be regarded as being realistic, favouring a particular barrier or being acceptable. No single test can replicate the range of variations in vehicle accidents for structural loading/behaviour and different high deceleration scenarios, and some differences are linked to characteristics that can have advantages.

Metrics: Two relatively new metrics are envisaged for phase 1a. The principle behind them is to encourage all vehicles to have a sufficiently strong structure within a common interaction zone. They consist of vertical and horizontal components. These are complementary but could be applied separately. Work to evolve the metrics has concentrated on the vertical one first and this will be followed by further analysis to propose a performance limit for the second. Both tests may evolve based on feedback from evaluations.

Vertical metric: This would particularly influence LTVs and is intended to benefit LTV to car structural interaction. The concept was to (a) set a target row load and (b) calculate the load below the target row for each row in the common interaction zone. The metric addresses areas where the force may be below a desired level; set out in mathematical terms it limits VNT (vertical (component) negative deviation from target row load). More simply, a minimum row load of [100 kN] is proposed. It is intended to be an indicator that an LTV has structure in alignment with the relevant rows and should also be achieved by cars, without the need to cap or adjust for small cars. TRL (EEVC) and Japanese analysis had suggested a value of about 100 KN. The proposal uses peak cell load values.

Horizontal Metric: The aim is to assess if crossbeam(s) or comparable structure on SEAS, have sufficient strength. The metric would encourage a crossbeam strength that tended to match the stiffness of the front of the longtitudinals. The concept for horizontal is (a) to set target cell load for the row based on overall (total) row load level and (b) calculate load below target cell load for each cell between the rails for each row in the common interaction zone.

So far analysis has been exploratory. The HNT deviation metric value distinguished stiff and soft bumper crossbeams in limited tests. A question of how strong a bumper crossbeam should be on large vehicles has been raised.

AHOF: NHTSA have shown a correlation between this metric and casualty risk in the existing US fleet. However AHOF alone is not felt to be sufficient to monitor some structural changes, in particular SEAS. It continues to be recorded in test work and remains a candidate phase 1a metric. A performance level has not been suggested. Japan has suggested that AHOF at the beginning of impact may be a more indicative measure of vehicle structural interaction potential.

European analysis of AHOF using a deformable face suggests a range of AHOF values with cars typically in the 400 to near 500 mm range. Two modified cars gave lower values than the original car. LTVs ranged from about 490 to 550 mm.

Repeatability: Two tests with a large family car were examined for repeatability and, though the peak force was 10% higher on one car, the VNT and HNT deviation metrics showed good repeatability e.g. vertical row (12%), horizontal (higher but on low numbers) for a 16 mm vertical and 14 mm horizontal difference in estimated impact alignment. However, because of the potential for impact alignment sensitivity, and generally, manufacturers have been asked to assess their vehicles to ascertain the robustness of the phase 1 test procedure. (In practice, at present this means phase 1a.) This could involve modelling as well as analysis of tests.

A pass level for a compatibility metric could be aimed at delivering improvements, while also taking some account of practical test factors. All regarded good control on vertical test accuracy as being important for repeatability. Test results from a number of laboratories were analysed for impact accuracy. Three labs with the closest results in this area currently achieve results inside a +/- 10 mm vertical band which would seem a reasonable target for a specific impact alignment tolerance on this aspect.

Close control of impact alignment in test conditions does not mean that safety performance need be similarly sensitive in practice if the alignment of a vehicle differs on the road. Phase 1a can help in the provision of load bearing structure in an area on LTVs where none may exist at present, helping in LTV to car impacts. In addition, the size or coverage of structures can be influenced in practice due to practical considerations such as crushing a barrier face over a wide enough area to generate a desired force and possibly catering for variation in ride height between model variants.

Issues

The main issues to be addressed are

- The degree to which the metric affects the fleet and the benefits of changing to meet phase 1
- Robustness of the test procedure (mainly impact alignment sensitivity of vehicles).

In addition there are aspects associated with further defining more specific or detailed aspects of the outline phase 1.

- Confirming the appropriateness of [100 kN], for example for small cars
- Proposing an appropriate value for the horizontal metric
- LCW specification and acceptance criteria (including measurement tolerance)
- Specification of deformable element (acceptance criteria e.g. control of segment strength)

Some will involve manufacturers looking at the degree to which the fleet would be affected and the benefit; this would draw on modelling work/ testing. Similarly, experience of the robustness of the procedure with real world vehicles is important. A LCW specification being prepared by NHTSA is covered later. The deformable element specification can draw on other hexcell controls.

The results of this work may lead to change or further evolution of the proposal.

Specification/ Acceptance Criteria For Load Cell Wall (LCW)

NHTSA are drafting a LCW specification and acceptance criteria. This builds on an internal procurement specification and offers a wider harmonised approach to LCW specification; this document was presented to the group. EEVC (UTAC, BASt) and industry fed back comments direct to NHTSA on issues such as dynamic acceptance testing, cell mounting techniques, facing material and resonant frequency. This has involved little group effort. Free air resonant frequency will be part of the specification. NHTSA are also investigating the effect of light and dense wood faces on the load cells.

Candidate Further Metrics - Phase 1b

A number of approaches could offer candidate metrics for further steps within a first phase. All are aimed at improving structural interaction. They offer either an alternative or supplementary assessments of structural interaction but, if desired, individual metrics could be used in any combination.

Potential Phase 1b candidate metrics are outlined below.

Relative Homogeneity: This would control the force distribution over a wider area beyond the common interaction area in Phase 1a, the aim being to encourage the development of structures that behave in a more homogeneous manner. This metric has been used in research analysis in VC-COMPAT and by IHRA members. Areas to be addressed for use as a metric include whether to use peak force or impulse, size of an assessment area and performance limits. (A more detailed discussion of relative homogeneity is in the Phase 2 section under the FWDB.)

Deformation Based: This would evaluate the degree to which a vehicle generates "sufficient support" within a common interaction area (same height range as in Phase 1a but width might differ). The proportion of the surface of the stiffer rear layer which is deformed in this area is determined and used as a measure of sufficient support being provided. Also, if this is suitably distributed between the top and bottom of the common area, then structures below it might be credited. An advantage is that it should be insensitive to impact alignment. An issue could be the accuracy with which the deformation imprint can be determined. The approach is being explored by European industry. An analysis of barriers from earlier tests with weakened, standard and reinforced crossbeams gave progressively higher proportions of the surface deformed (ranging from 23% to 43%). A series of evaluations of the deformation of barriers from earlier tests of standard vehicles is planned.

It is being researched as an alternative assessment technique to a force based assessment as in Phase 1a. However, the overall pattern of barrier deformation might also be considered as a means of obtaining information on the distribution of loads within the interaction area and supplementing a Phase 1a test.

Alternative Metrics with Assessment Area Extended Beyond Rows 3 and 4: In principle, any metric which focuses on rows 3 and 4, the common interaction area, could be extended to other rows, particularly row 2 for cars. Any approach should maintain an appropriate level for structural interaction in the common interaction area. The issue is not the concept, simply that the immediate priority in Phase 1a has been the common interaction zone. The two metrics (Relative Homogeneity and Deformation) already cover or can be extended into other rows. The heights of various vehicle structures including crossbeams, upper rails, lower rails and forward (long) subframes, from the European VC-COMPAT structural survey, are shown in Figure 2.

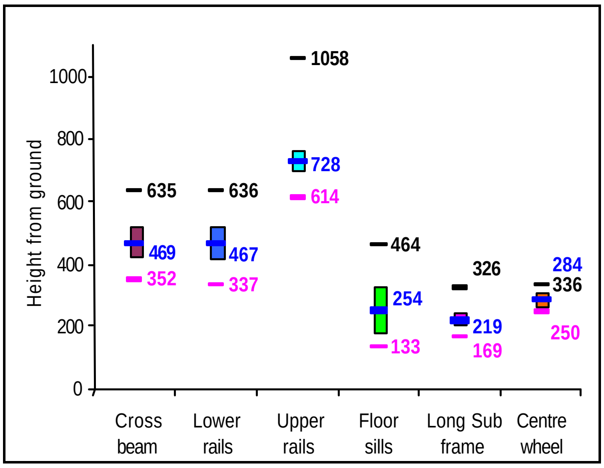

Figure 2. Height of various vehicle structures including crossbeams, rails, and forward subframes

Initial Stiffness

NHTSA obtained a correlation between this metric and casualty risk in the existing US fleet. The deformable element, because of its function, has different initial impact characteristics to a rigid wall and does not give the same initial stiffness value. (NHTSA and Japanese data confirm this.) However this does not mean that a comparable metric could not be derived on a revised basis for the deformable element but initial stiffness is not considered as a candidate phase 1b metric.

Potential For LCW Improvements (Increasing Resolution)

The (125 by 125 mm) size high resolution load cell continues to be appropriate. However, means of increasing resolution are being investigated with the aim of providing more information about the vehicle's structural characteristics. Three potential routes are outlined.

- Smaller load cells: If specified, this would be likely only in the common interaction zone, currently rows 3 and 4. For example the cell size could be based on 62.5 mm square or an oblong rectangle of 62.5 mm vertical and 125 mm horizontal.
- Measuring moment: Moments might be measurable across a load cell by using existing load sensing sub-elements within an individual load cell and one member is exploring this possibility. In addition NHTSA's simulation work aims to explore the use of this concept and has developed a technique to simulate moment measuring load cells.
- Supplementary deformation measure: This would use the pattern of deformation of the deformable element, in particular the rear layer, to give extra information on the forces applied e.g. whether the force was applied over specific parts or all of an individual load cell. The use of deformation as a supplementary technique was explored using modelling but the benefit was not as great as expected though the model may have been over-pessimistic.

The above deformation measure differs from the "sufficient support" deformation metric which makes an overall assessment of the zone whereas the assessment here was over the area of an individual load cell. However some extra information might emerge from work on the overall metric.

Finally, in addressing any potential advantages of a change to increase resolution, it would be necessary to bear in mind that increasing resolution might also mean a risk of decreasing the reliability of the test. For example, if the number of load cells is increased, apart from the cost, there is a corresponding increase in the risk that the signal output(s) from one might be lost.

POTENTIAL PHASE 2 TESTS (OUTLINE)

Outline Of Current Position

While the group agreed to focus on an IHRA Phase 1, it also wanted all options to remain open for Phase 2. For example Japan stressed the importance of addressing compartment strength. Work in member regions has continued to cover a range of potential tests outlined in this section, though the level and area of activity has varied depending on regional priorities and resources.

The potential tests include a continuation or evolution of a FWDB phase 1 step, extra information from the existing ODB test, a high speed compartment strength test, various PDB proposals and the longer term possibility, probably phase 2+, of an MDB. The position on these is summarised below. Inclusion does not mean that the group view is that a test would be included in any phase 2 proposal. The group intends to review longer term research in developing or evaluating these areas after ESV 2005. Some tests address individual aspects of compatibility. Others are based on an interpretation of an overall result which is influenced by several compatibility aspects of the vehicle. A full width high deceleration test would also feature in phase 2 test scenarios, including those of the EEVC, as a self-protection test. This section outlines the range of compatibility tests and some self protection tests that can offer relevant information or control.

Full Width Frontal Test With A Deformable Barrier Face (FWDB)

This 56 km/h test uses a load cell wall to assess and control the potential for structural interaction between vehicles. (It also offers a high deceleration test.) This is also the proposed phase 1 test configuration but the test metrics used would be developed further and the test could evolve. In the family of associated tests, additional information could be generated from other tests to control (within a range) the peak force generated in a self-protection ODB test and a high speed compartment strength test, possibly 80 km/h, purely to assess passenger compartment strength.

Evaluation work on the full width deformable barrier (FWDB) has concentrated on the ability to measure the forces generated by the car frontal structure and on the use of metrics to measure these. Currently for phase 1a, different metrics have been proposed. Work on a homogeneity assessment will continue as a possible phase 1b metric or further evolve for phase 2.

The approach being developed to assess the homogeneity of forces in a vehicle footprint, as seen by the barrier, is briefly described. A footprint area, provisionally based on the dimensions of the vehicle being tested, was chosen for the development and evaluation of a possible assessment measure. The method used smoothes the forces from each load cell within the area to minimise the problem of structural members bridging adjacent load cells, and quantifies the variation between each smoothed load cell force and a derived target load level over the footprint. The work to date has shown how the assessment measure can be used to calculate the variation between rows and columns to give an indication of vertical and horizontal homogeneity.

It can be sensitive to impact alignment accuracy for vehicles which have single load paths or where these dominate and examples have been found. But these are not homogeneous vehicles and this sensitivity should be less of an issue, if higher levels of homogeneity are required. One of the highest levels of homogeneity achieved to date was in a recent SUV test. Also higher LCW resolution could be advantageous in reducing any alignment accuracy sensitivity.

Other issues include determination of the assessment area, whether to use peak force or an impulse based approach. Recent work found impulse gave a similar distribution to that of peak cell force and the effect of localised spikes was reduced. On a more general note, the output lends itself to analysis of a specific aspect (structural interaction) directly. Also the output is available from the beginning of the impact should a particular stage or time factor be relevant.

Offset Deformable Barrier (ODB) Test

This high deformation self-protection test could be used to supply extra information for compatibility purposes using a LCW. (In current ODB tests, speeds range from 56 km/h in regulations to 64 km/h in several consumer tests.) The car's frontal stiffness could be controlled by specifying that the peak force should lie within a specified range.

Another avenue involves exploring whether data from a 64 km/h ODB test can be successfully used to give an indication of compartment strength.

High Speed Compartment Strength Test

This avenue is an ODB test at [80] km/h purely to assess compartment strength for small cars as there are concerns about the effect on heavy cars. There are no dummy requirements. This has been explored by the EEVC in earlier work, although further work is deferred in the current EEVC programme. Japan has recently reported some further overload tests in the context of a wider exploration of possible approaches.

In terms of the latter, Japan has continued to evaluate possible metrics that might be used to derive appropriate compartment strength information from a 64 km/h ODB test. These included maximum structural force, end of crash force (EOCF) and rebound force, each reflecting barrier force recorded at different points in the impact e.g. EOCF was defined as the barrier force at the time when the engine acceleration is minimum after the engine makes contact with a firewall. At present, there are issues with all the metrics and how to measure compartment strength remains open. Australia has also looked at rebound force in an analysis of some of its earlier PDB tests but this did not give a clear indication of compartment strength.

Progressive Deformable Barrier (PDB)

Overall Position: In the last ESV report, the PDB 60 km/h (for partner protection) was part of a second EEVC grouping of tests including a high deceleration 56 km/h full width test (self-protection) and a 60/64 km/h ODB (self-protection, high deformation). However, this could change as France is researching the use of the PDB as a self protection test to replace the current ODB (ECE Reg. 94, 56 km/h) test. This continuing research has been reported via the EEVC for information to the IHRA group. The French proposal is that a change should be made on self-protection grounds before any decision is made on whether the PDB barrier should be used for compatibility. The compatibility metrics are still being researched. There has been no substantial discussion as yet in IHRA, but compatibility and self protection aspects are likely to be part of any future IHRA phase 2 discussions, either as independent or linked PDB options.

The PDB test involves a 60 km/h ODB test with a Progressive Deformable Barrier (PDB) face and 50% overlap.

PDB for Self-protection: The latest French research is aimed at modifying the current ODB test (Reg. 94). The modifications proposed by France are to replace the existing (EEVC) deformable element with the PDB deformable element, change the test speed to 60 km/h and overlap to 50%. These are exactly the same conditions as in the compatibility test but now with dummy criteria and also potentially intrusion criteria; there would be no compatibility criteria but a compatibility proposal could be made later. Testing has been performed to compare three cases - regulation 94 (56 km/h), regulation 94 with an increased test speed of 60 km/h as recommended by EEVC WG16 and the French PDB proposal. France saw the main advantage of using the progressive barrier as having the test Equivalent Energy Speed (52 km/h EES) similar for different mass cars, which is not the case for the current EEVC barrier. The approach is aimed at improving the compartment strength of small cars, which would be subject to a more severe impact than at present in regulations, without increasing the severity for heavy cars.

Points raised in brief discussion/clarifications on the presentation included the likelihood that some control on the amount of energy that the barrier absorbs would be needed to ensure that all cars have the intended similar EES in this test. This control could be a mass dependent measure such as limiting the allowable average depth of deformation of the PDB to prevent light vehicles being engineered to take advantage of the large energy absorption capability of the barrier.

PDB for Partner Protection (Fixed Speed): The aim of the PDB offset test is to control a car's structural interaction and frontal stiffness up to an equivalent energy speed (EES) of about 52 km/h using measurements of the barrier's final deformation profile.

The PDB compatibility approach seeks to control two aspects by interpreting the final deformation pattern on the PDB face post impact; firstly, depth of deformation level associated with a desired control on maximum force and secondly structural interaction by a variation of depth measurement to reflect local force variations which are in turn linked to a height criteria. (More uniform deformation would indicate a more compatible structure.) The broad appraisal method is outlined below.

The barrier surface is first digitised. Separate areas from different regions of the face, which have the same degree of deformation, are grouped to give a total area for that deformation. A height is then associated with each grouped area. A good compatibility rating would be based on an appraisal which makes an overall assessment of performance, drawing on both deformation (force) and height criteria. The boundary chosen for evaluation excludes the edges of the barrier face, especially the outer edge which suffers additional deformation as the vehicle rotates around the barrier during impact.

Work continues to determine the best way to deal with these derived measures in a numerical appraisal method. The current formula for overall assessment, although available for research, is not ready to be proposed. UTAC is working on medium term measures for three parameters:

(1) Average Depth of Deformation (Stiffness)

(2) Average Height of Deformation (Geometry)

(3) Max deformation of barrier after ADOD line (Homogeneity)

In the medium term a new and different criteria could be a function of all three of these. Current indications are that interim steps would be proposed; the first proposal would be for a single measure which reflects a combination of AHOD and ADOD.

The PDB deformed barrier face (after impact) represents an overall total effect in which several vehicle compatibility factors have combined over the impact. Separating these factors reliably is the subject of the current work.

The PDB generates higher shear in both vertical and lateral planes. (Generating high shear may have advantages in testing structural interconnections between load paths.) Being an offset test, it involves greater structural deformation. Penetration of the barrier outer skin can sometimes occur which can give rise to further damage on removal of the barrier. This would make a rating more difficult but may not occur (or be permitted) if high level(s) of compatibility are specified in a test proposal.

PDB Constant Energy

This Australian approach uses the fixed PDB barrier in a constant energy test, the aim being to stiffen small cars and soften large cars, to control compartment strength and improve structural interaction. The test configuration is with 40% overlap, dummy criteria and a load cell wall behind the barrier. It would be carried out at constant energy with variable speed, equivalent to 48 km/h for 2.5 tonnes and no limit on speed e.g. 74 km/h at 1060 kg. Australia considered that the ODB may still be necessary for cars heavier than [1400] kg as these are not tested at high speed into the PDB.

Essentially this takes compatibility to a further stage in terms of the emphasis on small car occupant protection and compartment strength.

Mobile Deformable Barrier (MDB)

This approach offers the ability to provide for mass and carry out angled (oblique) offset tests. The US regards a mobile deformable barrier (MDB), in conjunction with existing tests, as offering improved coverage of US accidents and in a later phase could be used to address frontal impact and compatibility. The MDB, if considering frontal impact self-protection, would not ensure that all the energy can be absorbed in the vehicle frontal structure unless the MDB mass is increased for heavier vehicles.

There are options of one or both moving (MDB and vehicle). There are however practical considerations such as high test speed (if one moving), test laboratory capability and site approach distances (one or both moving). It would not equalise frontal force but the use of load cells offers information on frontal force and interaction which could be controlled.

There is no specific update on MDB testing since the last ESV report. Past work in Japan had suggested that the current face used could be investigated. Possibilities could include the PDB face. Any programme of MDB development would be a longer term exercise with greatest interest in the US, including a full width MDB; NHTSA pointed out that it could be useful to start early given the long timescales. Other members, despite differing experiences in the past, would also wish this to be included in a review of possible longer term work. However ensuring adequate self-protection for larger vehicles was a concern expressed by European and Japanese industry.

SOME ADDITIONAL ASPECTS/ FACTORS

Specific Test Requirements For Side Impact

The immediate priority for the group lies with tests to improve frontal compatibility. Improving some aspects of vehicle fronts may help in side impacts but comprehensive requirements aimed at side impact would be complex and a separate exercise, if possible.

Insurance Low Speed Damageability Test – Potential Developments

A presentation was made to the group by a representative from an insurance industry research centre on work by the Research Council for Automobile Repair (RCAR) to update the current low speed damageability test. Although the RCAR group have not yet fixed a bumper test height, the IHRA group felt that there could be a possible conflict on one aspect. If a consequence of the proposed insurance test was higher front bumper beams or associated structure than at present, it was felt that this would create an incompatibility with the lower front bumper beams found in the current fleet and the fact that the IHRA group were building on the use of the 581 zone, either directly or indirectly. If that happened, the result would be an increased risk that new cars with higher bumper or crossbeams would override existing cars with an associated likelihood of increased occupant injury.

OUTLINE AREAS FOR RESEARCH PLANS / NEXT STEPS

The following sets out a structure under which topics can be further discussed after ESV. It is also important to stress that further activities would naturally require agreement by the Steering Committee.

Possible Route Map Summary

The possible route map covers areas of research that could allow the definition of test and assessment protocols over short, medium and long term timescales.

(1) Within a short term (less than 2 years) timescale: Phase 1 test procedure to enhance structural interaction.

The following further areas were identified and are to be reviewed after ESV.

(2) Within a medium term timescale: These are likely to be fixed barrier tests aimed at improving compartment strength and frontal force matching and further improving structural interaction.

(3) Within a long term timescale: This is likely to be a mobile deformable barrier test.

CONCLUSIONS

Phase 1

The group agreed that, in principle, the outline test procedure described offers the best way forward for a harmonised phase 1 test proposal. The proposal aims to improve structural interaction primarily for LTV to car compatibility.

Recent phase 1 discussion has been mainly on a vertical metric to improve LTV to car compatibility. A later metric could address cross beam strength which could also benefit car to car compatibility but so far analysis has been exploratory.

This agreement in principle will be reviewed following further investigation of the proposal by group members. The main issues to be addressed are:

- The degree to which the metric affects the fleet and the benefits of changing to meet a phase 1.
- The robustness of the test procedure. (mainly impact alignment sensitivity of vehicles)

The use of a deformable element is an open question for Japan.

It is important to keep the outline test procedure for phase 1 in perspective as a potential first step. It must be viewed against a background of much wider longer term research which continues in an effort to develop further compatibility test procedures.

Phase 2

While the group agreed to focus on an IHRA Phase 1 test, it also wanted all options to remain open for Phase 2.

A range of phase 2 options are being explored. For example VC-COMPAT is concentrating on a full width test with a deformable element and a PDB approach; the associated EEVC recommendation is expected at the end of 2006.

The MDB is seen as the longest term option.

A special test or requirement for side impact is some way off although some aspects of a frontal test should help.

Wider Comments

The priorities are structural interaction, followed by compartment strength and control of frontal forces.

EEVC, NHTSA and other research programmes have different emphases but considerable common interest. The close links with the EEVC group work well and industry involvement has been a healthy aspect.

ACKNOWLEDGEMENTS

The spirit of co-operation and contributions of all those who have been involved in the work of the IHRA Compatibility and Frontal Impact Working Group are gratefully acknowledged. In addition, thanks is due to many others who made presentations either directly to the group or at meetings to which the group was invited.

NHTSA'S RECENT COMPATIBILITY TEST PROGRAM

Stephen Summers
Aloke Prasad
National Highway Traffic Safety Administration
United States
Paper Number 05-0278

ABSTRACT

NHTSA has developed and conducted a vehicle-to-vehicle crash test program to evaluate the statistical correlation between vehicle performance measures and the probability of driver fatality in a crash partner vehicle. The test program uncovered some concerns regarding NHTSA's rigid barrier data collection and review methods. The vehicle-to-vehicle tests did not provide clear insight into the mechanism behind the fleet correlation, but did emphasize the complexity of vehicle compatibility and the changing safety priorities related to improved occupant restraints.

INTRODUCTION

In September 2002, the National Highway Traffic Safety Administration (NHTSA) formed an Integrated Project Team (IPT) to conduct an in-depth review of vehicle compatibility [1]. This team was chartered to identify innovative solutions and recommend effective strategies to improve vehicle compatibility. One of the strategies developed by this team was to initiate a test matrix to investigate opportunities for vehicle crash partner protection. This paper documents the development, analysis, and results from this test program.

In recent years, NHTSA has conducted several crash test and statistical studies to evaluate vehicle compatibility. These studies attempted to correlate the results from staged crash testing with the fatality and injury consequences observed from the accident databases. The IPT recommended a vehicle-to-vehicle test program to explore the results published in the report, "Vehicle Weight, Fatality Risk, and Crash Compatibility [2]."

In this report, Kahane evaluated the fatality risk to the driver of a passenger car when struck by another passenger car or an LTV. The fatality risk for vehicle models were compared against compatibility measures derived from U.S. New Car Assessment Program (NCAP) testing. The average height of force (AHOF) and initial stiffness were evaluated as predictors of real world crash outcomes [3].

Kahane found that the difference in the AHOF between the struck and the striking vehicles had a statistically significant negative effect on the fatality risk to a car driver struck on the left side. A passenger car driver struck by a vehicle with a relatively higher AHOF would have a greater risk of fatality. No correlation was found by Kahane for front-to-front crashes, but subsequent research indicated that a correlation exists only for belted drivers struck front-to-front by a vehicle with a higher relative AHOF [4].

In addition to the geometric aspects of AHOF, Kahane evaluated the energy absorption or front-end stiffness of the striking vehicle. NHTSA had previously developed a methodology to compute a front-end stiffness measure from a linear fit to the force-deflection profile in NCAP testing [3]. Kahane found that the stiffness of an LTV had a statistically significant positive effect on the fatality risk for a passenger car driver struck in the front. The study also found that the stiffness of a striking car in a left side impact had a statistically significant positive effect on the fatality risk of the struck car's driver.

In order to evaluate these statistical results, it was desired to implement a vehicle-to-vehicle test program to evaluate how the striking vehicle characteristics affect the safety performance [5]. It was decided to use three classes of bullet vehicles: minvans, SUVs, and pickups. Two vehicles from each category were selected to have similar size and weight, but with different compatibility measures. These six bullet vehicles were tested in a series of vehicle-to-vehicle crashes against a single target vehicle. The occupant injury measures in the target vehicle were used to assess the compatibility of the striking vehicle.

TEST PROGRAM

It was desired to select a test program that closely resembled the fleet crash environment, but that also drew from industry standard practices, so the results could be readily interpreted. Data from the National Automotive Sampling System-Crashworthiness Data System (NASS-CDS) from 1998 to 2001 was evaluated [5]. NHTSA evaluated the frequency and distribution of impact angles, overlaps, and speeds. Comparing the crash data with industry practices, three tests series (full frontal colinear, 50 percent offset, FMVSS No. 214 configuration side impact tests) were selected. The full frontal and frontal offset tests were chosen to be conducted using the methodology described by Ford [6]. For these tests, the target vehicle is stationary and the bullet vehicle is towed at the appropriate speed to provide a 56 kph change in velocity for the target vehicle in the full frontal test. The same bullet vehicle speed is also used for the offset test. The colinear offset test is aligned for the bullet vehicle to engage 50 percent of the target vehicle. For the FMVSS No. 214 configuration tests, rear wheel assemblies are used to allow the bullet vehicle to be towed at a crabbed approach angle. There was discussion on whether to use the lateral NCAP impact speeds but in the end, the 214 speed was selected to allow comparison with previous NHTSA tests [7]. In total, 18 vehicle-to-vehicle tests were conducted. Each of the seven vehicles was also crashed into a 125 mm resolution load cell barrier to verify the AHOF and initial stiffness measures.

The bullet vehicles were selected as three pairs of similar vehicles, minivans, SUVs and full size pickups. The vehicle pairs were selected to have similar weight to minimize any mass effects that were not controlled by the test conditions. The vehicle pairs were also selected to maximize the differences between the AHOF and initial stiffness measures. For the SUV pair, the Chevrolet Trailblazer was selected as the higher, stiffer vehicle and was paired with the Ford Explorer. The Dodge Ram was selected as the higher, stiffer pickup and paired with the Toyota Tundra. For the minivan category, there was no ideal pair of recently tested minivans. The Dodge Caravan was selected as the higher but softer minivan and paired with the Chevrolet Venture. The target vehicle was selected on the basis of good NCAP and the Insurance Institute for Highway Safety (IIHS) offset performance. It was also decided to use a target vehicle with side curtain air bags. These safety countermeasures are expected to be more representative of future vehicles in the U.S. fleet.

After a review of recent NCAP tested vehicles, the 2004 Honda Accord was selected. When completed, the test matrix should provide data for evaluation of the vehicle crash partner protection initiatives that were identified in NHTSA's IPT report on vehicle compatibility.

HIGH RESOLUTION BARRIER TESTING

NHTSA has recently developed a new 125 mm high resolution load cell barrier for use in evaluating vehicle crash compatibility. For over twenty years, NHTSA has conducted frontal NCAP 56 kph rigid barrier testing. These tests measured the crash forces using a 4 by 9 load cell array. The load cell data from these frontal NCAP tests have been analyzed to evaluate performance measures that may relate to vehicle compatibility. The matrix of force measurements has been used to evaluate the height and distribution of crash forces for over 500 vehicle crash tests conducted under the NCAP program. It is desired to evaluate the crash results for the high-resolution barrier and compare the results against the lower resolution load cell barrier. These tests were intended to verify the previous data and to evaluate the increased resolution and geometric differences between the load cell barrier designs.

There are a wide variety of load cell barriers in use today. The barriers differ in size shape and in the layout of the load cell sensors. NHTSA, in conjunction with the International Harmonized Research Agenda (IHRA) Compatibility Working Group, has developed a standard load cell barrier configuration that would encourage broad comparison of load cell barrier results. The IHRA Compatibility Working Group has standardized on the use of 125 by 125 mm load cells. NHTSA has developed an 8 by 16 array of single axis load cells. Each load cell is rated for measuring up to 300 kN of compression. The test series was conducted with the barrier mounted 125 mm above the ground to be consistent with the Japanese Ministry of Land, Infrastructure, and Transport (JMLIT) NCAP program. Subsequently, the IHRA compatibility group recommended a standard height of 80 mm ground clearance. The 125 mm ground clearance used for this test series is higher than the older NHTSA load cell barriers, 67 mm. However, even this additional mounting height was not sufficient to engage the front structure of all seven test vehicles. Pre test alignments shown in Figure 1, demonstrated the potential of vehicle contact above the load cell array. The load cell barrier was augmented to create a partial ninth row using six spare load cells, as shown in Figures 1 and 2.

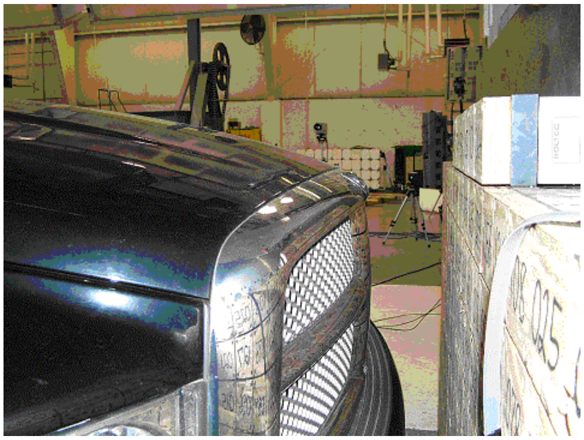

Figure 1. Pre test allignment for the Toyota Tundra

Figure 2. Load cell barrier augmented with partial ninth row

The vehicles tested in this test series are shown in Table 1. Only the Caravan was tested without the partial 9th row of load cells. The test numbers refer to the NHTSA Crash test database and can be used to obtain the complete test results [8].

Table 1. Rigid Barrier Test Vehicles

Test	Year	Make	Model	Speed (kph)	Weight (kg)
5062	2004	HONDA	ACCORD	56.6	1624
5087	2001	CHEVROLET	VENTURE	56.3	1975
4990	1996	DODGE	CARAVAN	56.3	1976
5034	2002	FORD	EXPLORER	56.3	2263
5036	2002	CHEVROLET	TRAILBLAZER	56.7	2339
5073	2002	TOYOTA	TUNDRA	56.3	2422
5061	2002	DODGE	RAM	56.4	2582

The vehicles in Table 1 were based on previous results from NCAP frontal barrier tests. The initial NCAP tests are shown in Table 2 below and will be used to compare results against the high-resolution data. The NCAP test for the Honda Accord was run at MGA using their load cell barrier, which has a 2 by 3 matrix of force measurements. The MGA load cell data is only used to compare total force measurements due to the limited spatial resolution. The NCAP tests for the Chevrolet Venture and Ford Explorer were conducted at Karco, Inc. At the time of these tests, the fourth row of the Karco load cell barrier was not working. These two tests only include measurements from the lowest 3 rows of the barrier. Additionally, one of the columns was inoperable for a total of 24 load cell measurements. The missing column of force measurement did not appear to be significant, but it appears that the missing 4th row of load cell data may have had significant consequences, particularly for the Ford Explorer test.

Table 2. NCAP frontal barrier tests

Test	Year	Make	Model	Speed (kph)	Weight (kg)	Load Cells
4485	2003	Honda	Accord	55.8	1571	6
3676	2001	Chevrolet	Venture	55.8	1971	24
2997	1999	Dodge	Grand Caravan	56.3	2011	36
3730	2002	Ford	Explorer	55.3	2323	24
4244	2002	Chevrolet	Trailblazer	56.49	2348	36
3915	2002	Toyota	Tundra	56.2	2401	36
4240	2002	Dodge	Ram1500	56.5	2518	36

Figure 3 shows an overlay of the high-resolution and NCAP barriers. The NCAP barrier is slightly wider and is mounted lower, 67 vs. 125 mm. The increased height of the high-resolution barrier may have been important for the taller vehicles. The NCAP barriers provide a reaction surface above the load cell array, flush with the load cell face. The narrower width of the high-resolution barrier appeared to be adequate for all vehicles in this initial test series.

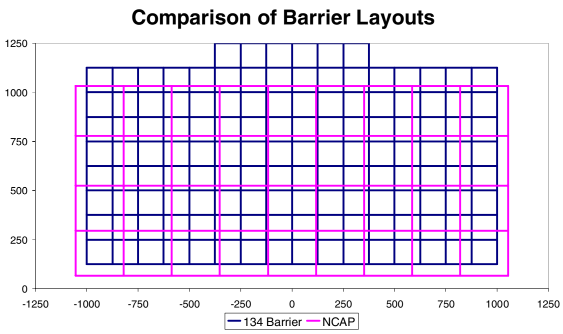

Figure 3. Comparison of NCAP and HR barriers

Total Force

In general, the total force time history measurements compare well between the NCAP and high-resolution (HR) test series. For all tests, the total force from each pair of tests displays a similar shape, duration and amplitude. The larger LTVs, particularly the Explorer and Ram, show more significant deviations between the two tests series. The Explorer HR test has a higher initial peak and the force drops off quicker after 50 ms. The Dodge Ram HR test has higher force than the NCAP test throughout most of the test, particularly between 60 and 80 ms. The front-end profiles for the seven vehicles are shown in Figure 4 below. The heavy line from 125 to 1125 mm on the Y-axis indicates the height of the HR load cell barrier. The three tallest vehicles in the test series all measured a peak force near 50 kN on the 8^{th} row of the HR barrier. The Toyota Tundra measured a peak force greater than 20 kN on the partial 9^{th} row of the HR barrier. The comparatively high peak force measured in the Tundra barrier tests may present an increased likelihood of intrusion for crash partner vehicles.

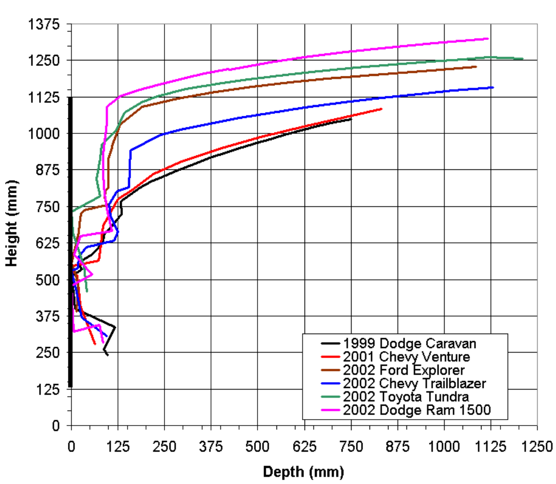

Figure 4. Vehicle Profiles

The correlation factor was computed to provide a numerical estimation for the similarity between the total force measurements. The correlation factor is an estimate of the likelihood that two signals could be equivalent with a linear transform. For two signals F(t) and G(t), the correlation factor is computed according to Equation 1 [9]. The correlation factor was computed from time 0 until one of the test vehicles reached zero velocity.

$$CF = \frac{\sum_{i=1}^{n} F_i G_i}{\sqrt{\sum_{i=1}^{n} F_i^2}\sqrt{\sum_{i=1}^{n} G_i^2}} = \frac{\sum_{i=1}^{n}\left(F_i - \overline{F}\right)\left(G_i - \overline{G}\right)}{\sqrt{\sum_{i=1}^{n}\left(F_i - \overline{F}\right)^2 \sum_{i=1}^{n}\left(G_i - \overline{G}\right)^2}} \quad (1)$$

The correlation factors between the HR and NCAP total force measurements range from 98.6 to 99.8. This supports the general observation that the shape, amplitude and duration are similar for both test programs.

One of the principle quality checks for the historical load cell data was to evaluate the total force data against vehicle accelerometer measurements. Assuming the vehicle’s mass does not change during the crash, the integral of the total force divided by the vehicle mass should approximate the velocity time histories measured by the vehicle accelerometers. This qualitative evaluation was used extensively for reviewing the historical NCAP test data [10], and was the basis for accepting the data from barrier tests with only 3 rows of load cell measurements. Generally tests with erroneous load cell or accelerometer data can be readily identified by the divergence of the accelerometer and load cell velocity estimates. Most of the NCAP and HR tests show good comparison between the velocity data. The Ford Explorer NCAP test shown in Figure 5 mildly under-predicts the velocity change, indicating that most of the force was measured through the lower 3 rows of the NCAP barrier.

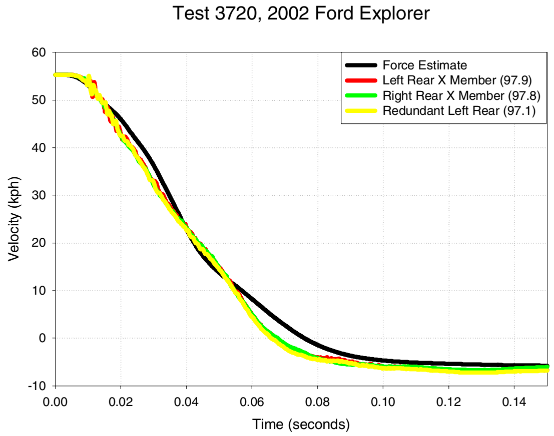

Figure 5. Velocity check for Ford Explorer NCAP test

The correlation factor was also used to compare the accelerometer and load cell derived velocity signals. The correlation factor was computed between time zero and the time when the force estimated velocity crossed zero. Historical review of NCAP test data have shown that the correlation factor is generally > 0.98. Additionally, a correlation factor below 0.95 often indicated a problem with the test data. Conversely, a correlation factor greater than 0.95 did not provide an additional estimate of data accuracy. Figure 6 below shows the correlation coefficients for the velocity estimates. The NCAP and HR barrier tests are generally in the same range for the correlation coefficiant. Of the high resolution tests, only the Ford Explorer had a correlation coefficient below 0.99.

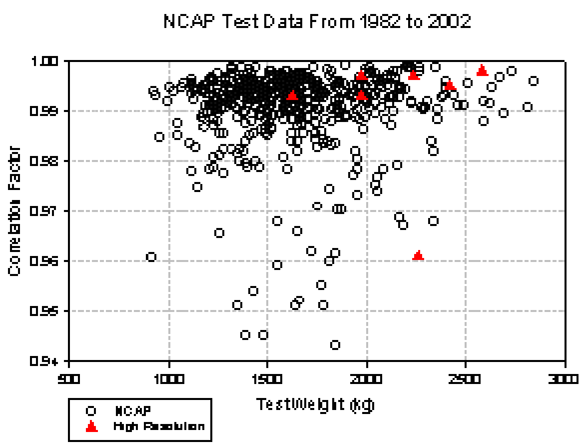

Figure 6. Velocity correlation factors for NCAP and high resolution barrier tests

Evaluation of the total force measured in the NCAP and high-resolution test programs raised some concerns regarding the repeatability of the total force measurements. The increased height of the high-resolution barrier and the loads measured in this region seem to indicate that previous NCAP testing did not measure all of the crash forces for the large LTVs.

Height of Force

The AHOF is a measure of the characteristic height at which the vehicle loaded the barrier during the test. At each time step, the Height of Force (HOF) is computed as shown in Equation 2 below, where n represents the number of load cells in the barrier. The HOF(t) represents the height which the total force should act to produce an equivalent moment about the ground.

$$HOF(t) = \frac{\sum_{1}^{n} Fi \times Hi}{\sum_{1}^{n} Fi} \qquad (2)$$

The HOF(t) is then averaged, using the total force(t) as a weighting function. The weighting function biases the AHOF to the time(s) when the force is highest. The resulting AHOF can be considered the characteristic height at which the force was transferred to the barrier during the crash. The AHOF is computed using Equation 3.

$$AHOF = \frac{\sum_{0}^{t} HOF(t) \times F(t)}{\sum_{0}^{t} F(t)} \qquad t = time\,step \qquad (3)$$

The HOF(t) and the AHOF can only be computed for times when the total force is not near zero. At the beginning or end of the crash, a low total force can lead to numerical instability in the computation. The AHOF for all of the tests was computed over the time duration where the total force exceeded 50 kN. The AHOF for the NCAP and HR tests are shown in Table 3 below. The AHOF is not shown for the Accord NCAP test, which was conducted using the 2-row load cell barrier at MGA Research.

Table 3. AHOF measurements

	NCAP AHOF	HR AHOF	Change (mm)
Honda Accord		414.5	
Chevrolet Venture	449.0	496.0	47.0
Dodge Caravan	534.0	553.0	19.0
Ford Explorer	495.5	593.4	97.9
Chevrolet Trailblazer	561.2	562.8	1.6
Toyota Tundra	516.9	575.6	58.7

Dodge Ram	570.1	587.7	17.6

The variation in AHOF between the NCAP and HR tests varied between 1.6 and 97.9 mm. The large discrepancy for the Explorer and Venture tests are likely due to missing fourth row of load cell data in the NCAP test. However, the Tundra test had complete NCAP data but had a 59 mm difference in the AHOF. This would lead to the conclusion that the relative size of the barriers and test vehicles leads to the higher AHOF's for the HR barrier. However, the Ram, Trailblazer and Carvan, demonstrated much lower AHOF differences. The vertical impact point was not measured for this test series, but was shown on subseqent test series to vary as much as 20 mm from the static pretest alignment. The AHOF repeatability is also limited by the approximately 250 mm load cell size for the NCAP tests. If the AHOF can only be expected to be accurate to within ¼ of the load cell size, then only the Explorer exceeds the accuracy expectations.

Figure 7 shows the HOF(t) for the Honda Accord as the green line. The AHOF is indicated by the dashed red line in Figure 7. The blue curve shows a running average for the HOF(t) and visually indicates how the AHOF converges to its final value. There is a large difference in the HOF(t) for the early and late phases of the crash. This behavior is typical for passenger vehicles where the engine generally impacts the barrier late in the crash.

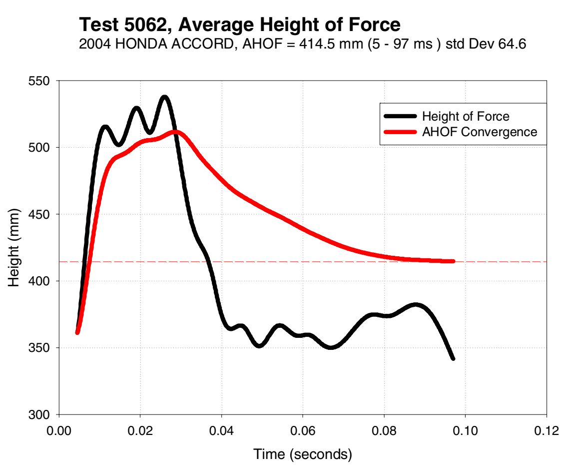

Figure 7. HOF(t) and its convergence for the Honda Accord

The change in HOF(t) for the Accord test can also be observed by examining the forces on the individual rows of the barrier, shown in Figure 8. The barrier rows are numbered from the bottom and increase upwards. Thus the row 1 curve is the lowest row from 125 to 250 mm above the ground. Evaluation of the test film indicates that the secondary impact measured by rows 1 to 5 resulted from the engine striking the load cell barrier.

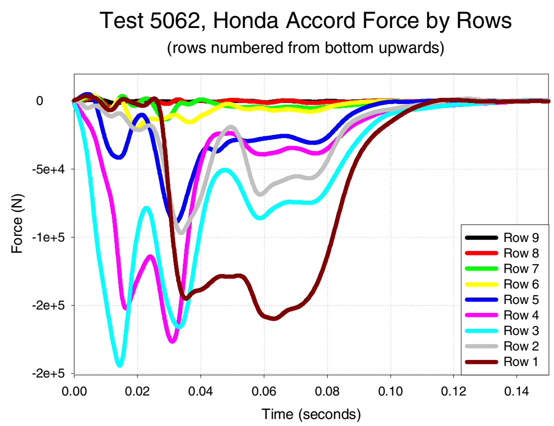

Figure 8. Row forces for the Honda Accord test

By comparison the HOF(t) plot for the Dodge Ram converges quickly to its final value as shown in Figure 9. The HOF(t) does not vary significantly until near the end of the crash.

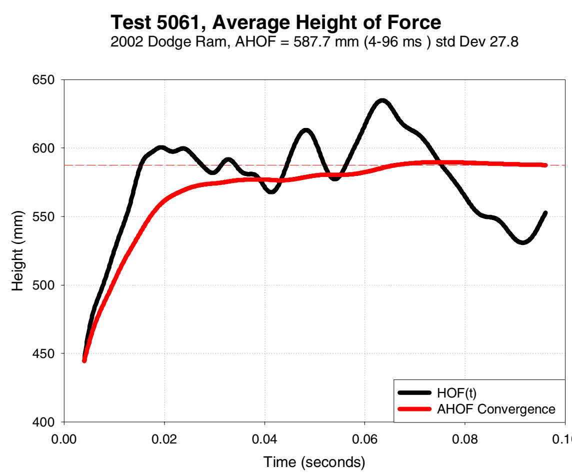

Figure 9. HOF(t) and its convergence for the Dodge Ram

The Dodge Ram measured most of its force in Rows 3 and 4 with smaller contributions from rows 5 and 8 as shown in Figure 10. The relative magnitudes of the row forces remained constant contributing to the stable HOF(t). Row 8, shown in blue, measured 13 percent of the peak row force. Row 8 is almost completely above the standard NCAP barrier and this force is data that would not have been measured in an NCAP test, but would have been transmitted to the plate above the NCAP barrier. Rows 8 and 9 had a peak force that was about 5 percent of the peak total force for the SUV and pickup tests. These high impact forces certainly contributed to the increased AHOF measured in all of the high resolution barrier tests.

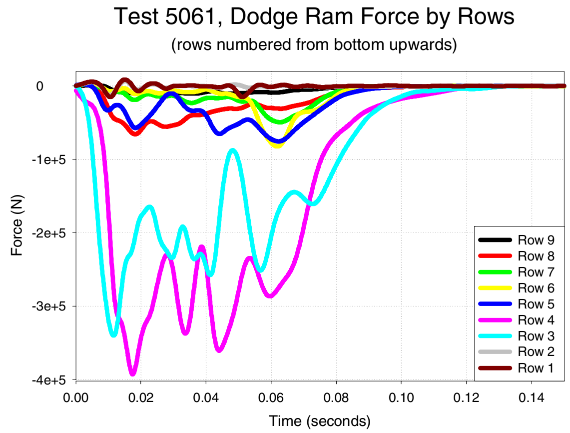

Figure 10. Row forces for the Dodge Ram test

Initial Stiffness

The initial stiffness metric was developed to characterize the initial slope of the force deflection profiles measured in rigid barrier testing. This is of interest because examination of the force-deflection profiles measured in NCAP frontal barrier tests indicated a consistent variation in the initial slope between cars and LTVs. Force deflection profiles were computed for each NCAP test. The profiles were then averaged by vehicle categories using the vehicle test weight. The average profiles are shown in Figure 11. The legend lists the vehicle categories and the number of NCAP tests that were averaged to compute the force deflection profile.

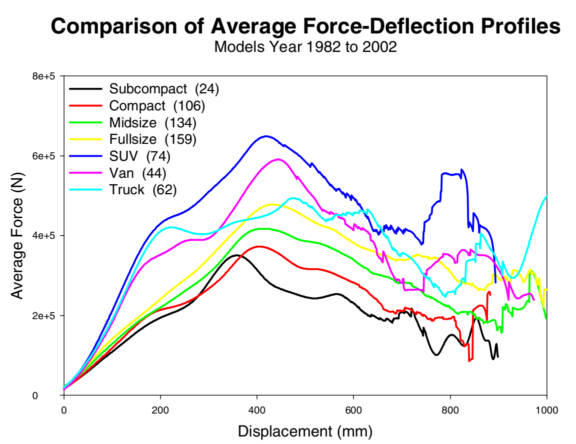

Figure 11. Average force-deflection profiles from NCAP test data

From 0 to about 200 mm of deflection, the average slope for SUVs, pickups and minivans were very similar and much higher than the corresponding slope for the passenger cars. The initial stiffness measure was developed to provide a numerical measure of this difference between passenger vehicles and LTVs. It was hypothesized that the initial rise in force could lead to increased door intrusion velocity in a side struck vehicle. Several methodologies were evaluated to systematically estimate the early slope in the force deflection profile [3]. The resulting initial stiffness was estimated by computing a linear fit that was constrained to start within the first 200 mm of the force defletion profile. The linear fit must have an R^2 value > 0.95. The slope of the longest straight line, greater than 75 mm in length was selected as the initial slope for the force deflection curve. The initial stiffness was computed for each of the NCAP tests and is plotted in Figure 12 below.

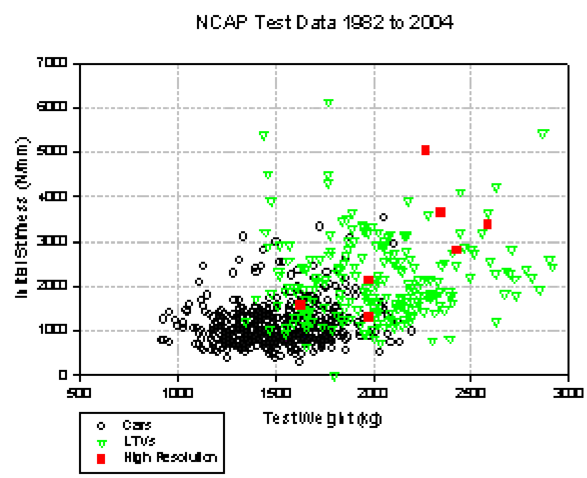

Figure 12. Initial stiffness measures for barrier tests

The initial stiffness measures for this test series are shown in Table 4 along with the earlier results from the NCAP testing program. Similar to the AHOF measures, almost all of the stiffness measures increased in the HR test program. The HR Explorer had a dramatic increase in stiffness compared to the NCAP test. Table 4 shows the percent change relative to the HR stiffness measures.

Table 4. Initial Stiffness measures

	NCAP Stiffness	HR Stiffness (N/mm)	Change
Honda Accord	1467.6	1593.1	7.9 %
Chevrolet Venture	1852.7	2146.4	13.7 %
Dodge Caravan	1347.0	1333.4	-1.0 %
Ford Explorer	2722.0	5002.8	45.6 %

Chevrolet Trailblazer	2478.8	3663.6	32.3 %
Toyota Tundra	1641.5	2829.3	41.2 %
Dodge Ram	2731.5	3401.0	19.7%

Figure 13 shows the significance of the increased initial force for the Ford Explorer. The initial stiffness regressions are shown as dashed lines over the force deflection profiles. The length of the lines indicates the longest applicable region with an $R^2 >$ 0.95. The high-resolution test has considerable more energy or area under force-deflection profile.

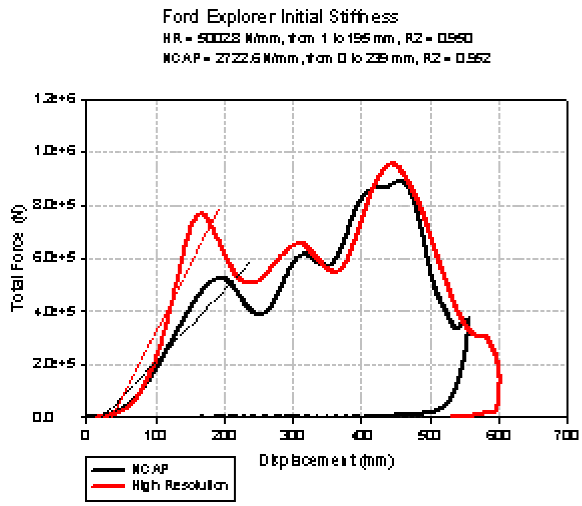

Figure 13. Initial stiffnes for the Ford Explorer

The initial stiffness for the Toyota Tundra tests demonstrated one of the shortcomings of using regression estimates, as shown in Figure 14. In the NCAP test, the inflection between the first two peaks of the force-deflection profile was small enough where it was possible to fit a straight line across the two peaks, resulting in a lower stiffness estimate. The high-resolution test had a more pronounced, or curved, inflection point which prevented a linear regression from spanning the two peaks.

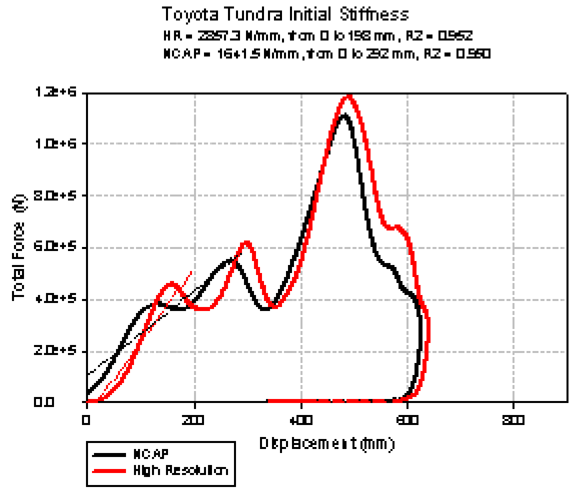

Figure 14. Initial stiffness for the Toyota Tundra

Overall, these test results raise some concern about the calculation of the initial stiffness measure from the NCAP test data. All but one of the vehicles had higher initial stiffness measures in the high-resolution test series. If this trend is consistent, then fleet correlation studies will have been conducted using underestimated stiffness values for the striking SUVs and pickups.

Injury Measures

The injury measures for the 50th percentile male drivers are shown below in Table 5. The injury measures are generally low with the exception of the Venture HIC15. This occurs between 69 and 84 ms when the driver's head appears to bottom out the air bag.

Table 5. Driver injury measures

Model	15 ms HIC	Max Nij	3 ms Clip	Chest Def	Left Femur	Right Femur
ACCORD	310.7	0.21	41.0	33.4	319	727
VENTURE	731.0	0.44	39.1	28.8	5366	8720
CARAVAN	553.4	0.53	51.7	40.4	6285	7336
EXPLORER	427.8	0.52	54.4	33.3	6486	6077
TRAILBLAZER	443.7	0.55	57.5	37.9	6111	6157
TUNDRA	352.9	0.36	47.9	31.4	3722	3475
RAM	381.8	0.30	48.0	33.6	2366	3508

The corresponding injury measures for the belted 5th percentile passenger are shown in Table 6. There were three injury criteria exceeding the reference values, the Caravan left femur compression, the Trailblazer 3 ms chest acceleration, and the Ram Nij in tension-extension (between 60 and 80 ms). The neck extension moment for the Ram passenger exceeded 28 N-m between 50 and 80 ms. The Trailblazer 3ms Clip occurred between 63 and 66 ms and had a peak Neck extension moment of 38 N-m at 55 ms.

Table 6. Passenger injury measures

Model	15 ms HIC	Max Nij	3 ms Clip	Chest Def	Left Femur	Right Femur
ACCORD	237.0	0.41	42.4	29.6	888	293
VENTURE	243.6	0.44	46.4	25.4	3275	2881
CARAVAN	586.8	0.35	50.4	14.4	6897	3724
EXPLORER	259.2	0.43	53.6	27.9	2194	1361
TRAILBLAZER	568.3	0.98	66.8	36.1	4798	3026
TUNDRA	695.8	0.47	59.3	29.9	3630	858
RAM	275.6	1.17	50.3	37.4	4878	1199

Intrusion Measurements

The intrusion measurements for the seven vehicles are plotted in Figure 15. The Venture generally had the largest intrusions with the two instrument panel intrusions in the IIHS marginal region. The brake pedal for the Caravan and Trailblazer were in the IIHS good region, along with both Instrument panel measurements for the Explorer.

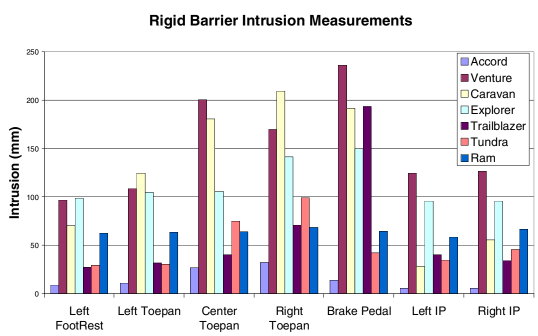

Figure 15. Intrusion measurements for high resolution barrier tests

Rigid Barrier Conclusions

The high-resolution load cell barrier appears to have operated properly and provided good data for the seven tests in this series. The peak forces were less than 2/3 of the rated load cell capacity. The 125 mm load cell has provided improved resolution. This series did bring into question the compatibility measures derived from previous NCAP test data. Significant load was measured above the standard load cell barrier. As a result, neither the AHOF nor the initial stiffness measures demonstrated test-to-test consistency. Repeat tests using the 125 mm barrier will be necessary to evaluate repeatability of these peformance measures. The test vehicles were selected to have a distribution of performance metrics. The HR barrier tests indicated that the performance metrics for the vehicle pairs were not as different as expected from NCAP test results. Figure 16 shows the AHOF and initial stiffness from the NCAP and HR barrier tests. For all three vehicle pairs the difference in AHOF for the HR tests is reduced as shown by the AHOF difference between the pairs of outlined and filled markers in Figure 16.

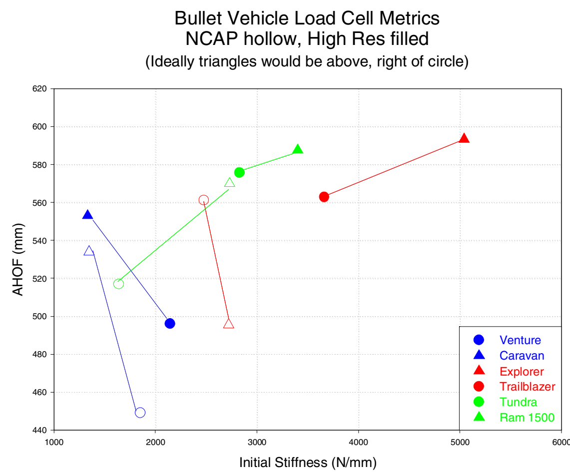

Figure 16. Distribution of compatibility measures for vehicle pairs

FULL FRONTAL VEHICLE TO VEHICLE

Six full frontal vehicle-to-vehicle tests were conducted. Each test was run against a stationary 2004 Honda Accord. The impact speed was established to obtain a 56 kph change in velocity for the struck Honda Accord. The test matrix is shown in Table 7 below. The Honda Accord contained a 50th percentile Hybrid III driver with Thor-Lx legs. The target vehicle also contained a 5th percentile female Hybrid III right front passenger.

Table 7. Full Frontal Bullet Vehicles

Test	Year	Make	Model	Weight Ratio	Speed (kph)
5109	2001	CHEVROLET	VENTURE	1.20	102.0
5112	1999	DODGE	CARAVAN	1.22	101.2
5081	2002	FORD	EXPLORER	1.41	95.6
5113	2002	CHEVROLET	TRAILBLAZER	1.46	94.5
5085	2002	TOYOTA	TUNDRA	1.48	93.8
5041 5247	2002	DODGE	RAM 1500	1.56	92.5

There was moderate override early in the tests with the SUV and pickup vehicles as shown in Figure 17. Overall, the crash interaction was very good with no signs of significant occupant compartment intrusion and good structural interaction between the target and the bullet vehicles.

Figure 17. Full frontal Tundra into Accord test

The normalized driver injury measures are shown in Table 8. below. In two of the tests, number 5112 and 5041, the driver air bag ripped during deployment. Honda repeated the test for the Ram and those results are shown in Table 8. No driver injury measures are available for the Caravan test.

Table 8. Injury measures for Honda Accord drivers in full frontal tests

Test	Striking Vehicle	15 ms HIC	Max Nij	3 ms Clip	Chest Deflection	Left Femur	Right Femur
5062	Rigid Barrier	310.7	0.21	41.0	33.4	319	727
5109	Venture	169.7	0.24	36.0	32.8	1231	2038
5081	Explorer	508.8	0.31	43.9	29.4	3280	5110
5113	Trailblazer	273.0	0.27	35.4	27.6	1896	2269
5085	Tundra	805.1	0.31	46.5	29.9	1249	5218
5247	Ram 1500	212.1	0.42	40.4	29.7	3589	2875

The test with the Tundra has a high HIC15 between 85.8 and 100.8 ms when the dummy's head appears to bottom out the air bag and hit the steering wheel. The driver struck by the Explorer had higher injury criteria for all injury measures than the driver struck by the lower, softer Trailblazer. There was no similar trend for the pickups.

Figure 18 plots the normalized injury measures for the Accord drivers struck by vehicles with the higher AHOF / Stiffness against the same criteria for the lower measures of each pair. The Explorer had higher AHOF and stiffness and generated higher Honda driver injury criteria than the Trailblazer. The Ram had a higher AHOF and stiffness, yet generated lower Honda driver injury criteria compared to the Tundra. The two vehicle pairs provide opposite conclusions in this test series.

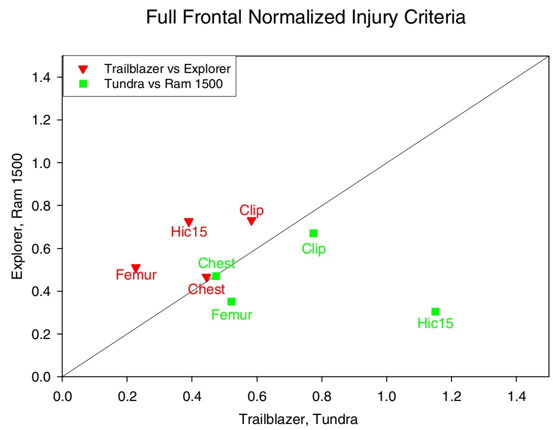

Figure 18. Normalized injury for vehicle pairs

The safety systems performed well for all of the Honda Accord passengers. The injury measures are generally low as shown in Table 9. For the two Ram tests, the Honda passenger injury measures repeated remarkably well. There are no observed trends between the passenger injury measures and the striking vehicle characteristics.

Table 9. Injury measures for Honda Accord right front passengers in full frontal tests

Test	Striking Vehicle	15 ms HIC	Max Nij	3 ms Clip	Chest Def	Left Femur	Right Femur
5062	Rigid Barrier	237.0	0.271	42.4	29.6	888	174
5109	Venture	242.6	0.264	44.8	16.4	2166	2291
5112	Caravan	224.9	0.332	42.3	18.2	2884	2337
5081	Explorer	282.2	0.283	47.3	15.7	3619	3503
5113	Trailblazer	155.3	0.383	35.2	16.3	3483	3716
5085	Tundra	218.4	0.502	45.5	16.5	3680	2882
5041	Ram 1500	255.2	0.321	43.9	14.9	3391	3232
5247	Ram 1500	286.7	0.297	48.1	17.0	3891	2259

Intrusion Measurements

The intrusion measurements for the struck Honda Accords are shown in Figure 19. The SUV and pickup striking vehicles produced considerably more intrusion than the two minivans. Only the Accord struck by the Ram exceeds the IIHS limits for good performance at the right toe pan and brake pedal locations.

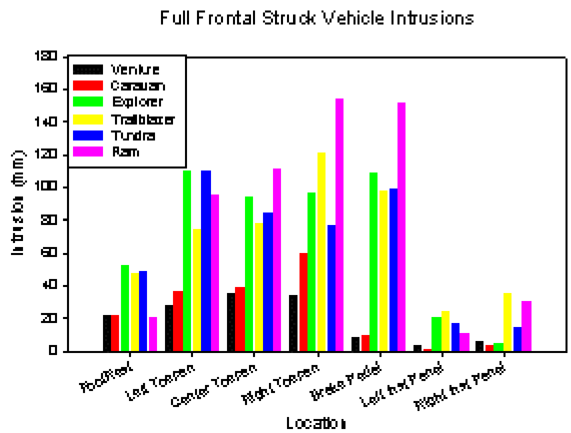

Figure 19. Full Frontal Intrusion measurements

The low intrusions for the minivan tests can be understood by examining the intrusion measurements for the striking vehicles, shown in Figure 20. Here the minivans clearly stand out as having significantly more intrusion than the SUVs and pickups. The Venture had brake pedal and instrument panel intrusions that exceeded the the IIHS good region. The striking and struck vehicle intrusions for the minivans tests are completely opposite of those measured in the SUV and pickup tests.

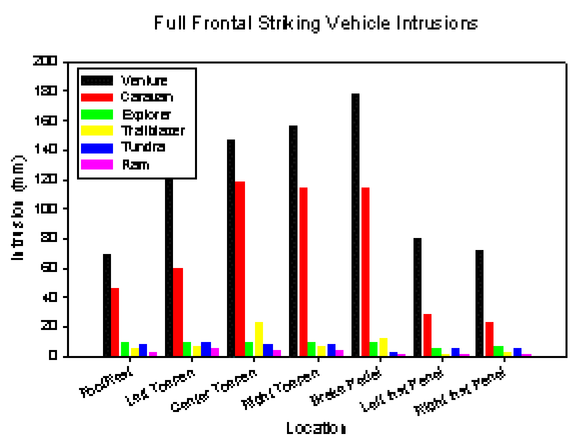

Figure 20. Full frontal striking vehicle intrusion

Comparison of Crash Pulses

Figure 21 plots the acceleration measured near the Honda Accord driver seat for all six of the full frontal tests. The acceleration for the rigid barrier test is also shown as the dark green line. The full frontal tests are suprisingly similar to the rigid barrier test. The vehicle-to-vehicle accelerations appear to have a slightly shorter duration. This is consistent with the passenger injury measures which were fairly consistent for all tests. Only the femur force measurements were consistently higher for the driver and passenger dummies.

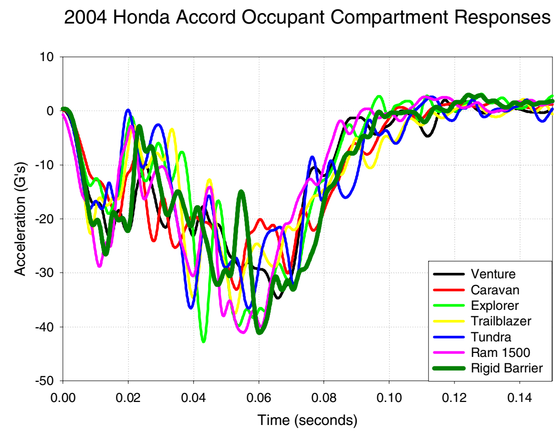

Figure 21. Comparison of Honda Accord acceleration measurements

FRONTAL 50% OFFSET TEST SERIES

An identical series of bullet vehicles were run into a stationary Honda Accord using the same impact speeds as the full frontal test series. In this test series, the vehicles were aligned so that the bullet vehicle would engage 50 percent of the width of the Honda Accord. The collinear offset test matrix is shown in Table 10.

Table 10. Offset Test Matrix

Test	Year	Make	Model	Test Weight	Speed (kph)
5110	2001	CHEVROLET	VENTURE	1943	102.8
5116	1999	DODGE	CARAVAN	2015	100.9
5080	2002	FORD	EXPLORER	2292	94.6
5040	2002	CHEVROLET	TRAILBLAZER	2371	93.0
5086	2002	TOYOTA	TUNDRA	2431	93.8
5111	2002	DODGE	RAM1500	2527	92.9

There were no test anomalies in the offset test series. The injury criteria for the Honda Accord drivers in the Honda Accord were all generally low and are shown in Table 11. For comparison the injury measures from an IIHS 64 kph offset deformable barrier test are included.

Table 11. Injury measure for Honda Accord drivers in offset frontal tests

Test	Striking Vehicle	15 ms HIC	Max Nij	3 ms Clip	Chest Def	Left Femur	Right Femur
4450	IIHS ODB	290.8	0.329	40.7	31.3	444	645
5110	Venture	273.4	0.215	37.9	28.1	1207	1965
5116	Caravan	387.6	0.302	38.6	26.4	1916	2243
5080	Explorer	264.9	0.330	40.5	33.4	3787	3967
5040	Trailblazer	282.1	0.347	46.2	28.7	3338	4325
5086	Tundra	240.2	0.237	35.2	26.3	3262	3117
5111	Ram 1500	184.9	0.234	33.7	26.4	2763	2418

The struck driver injury measures do not show a consistent trend between the striking vehicle characteristics. Figure 22 plots the normalized injury measures for the vehicle pairs. The injury measures generally fall along the 45 degree line indicating similar outcomes for the Accord drivers struck by the higher/stiffer and lower/softer vehicles.

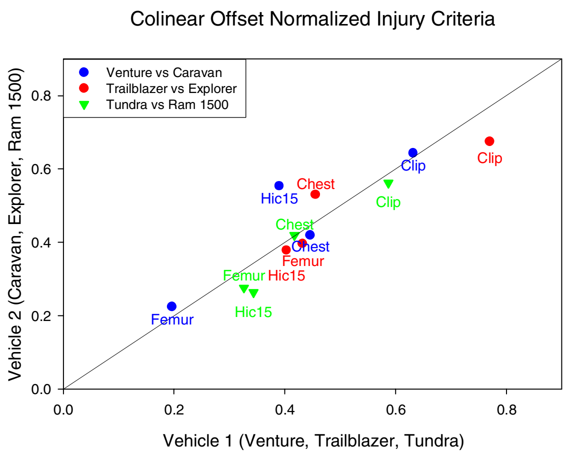

Figure 22. Normalized injury measures for the offset vehicle pairs

The Honda Accord 5th percentile female passenger dummies all had low injury measures and are not shown. The only significant injury measures recorded in this test series were for the drivers of the striking minivans. Both of the minivan drivers had HIC15 values above 90 percent of the accepted reference value.

Intrusion Measurements

Figure 23 shows the intrusion measures for the Honda Accord vehicles that were struck by the various bullet vehicles. The Accord struck by the Explorer had both instrument panel intrusions in the IIHS poor range. The Accord struck by theTundra had left and right toepan intrusions in the IIHS poor range. Only the Accord struck by the Venture had intrusion measurements completely in the IIHS good range.

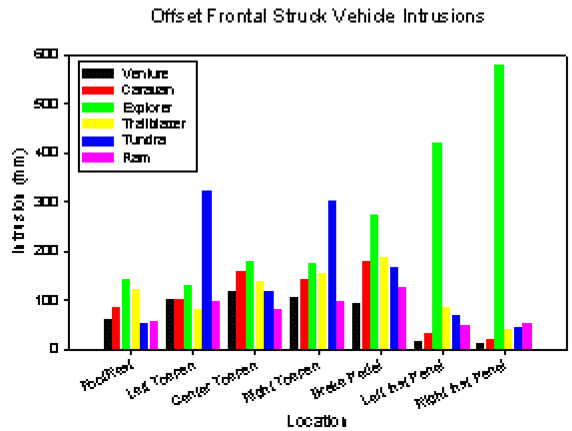

Figure 23. Honda Accord intrusion measurements

The low intrusions measured in the Accords struck by the minivans can again be understood by examining the striking vehicle intrusions shown in Figure 24. Here the Venture has several intrusion measurements in the IIHS unacceptable range. The intrusion measurements for the Caravan are in the IIHS acceptable range. All of the SUVs and pickups have minimal intrusion and are in the IIHS good range.

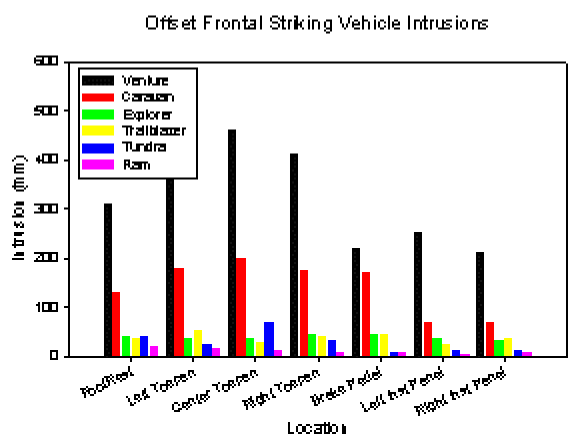

Figure 24. Striking vehicle intrusions

SIDE IMPACT TEST SERIES

The final test series in the program used the same bullet vehicles in FMVSS No. 214 configuration side impact tests. The Honda Accords were struck in the driver's side. An ES2re driver dummy was used. A SID-2S FRG dummy was seated in the left rear seating position. All tests were run at the same nominal impact speed, 54 kph, regardless of the mass of the striking vehicle.

Figure 25. Tundra into Accord side impact test

The injury measures for the struck drivers of the Honda Accords are shown in Table 12 below. This table also includes the injury measures from a FMVSS No. 214 configuration test conducted using a ES2re driver dummy in a Honda Accord. Almost all of the peak rib deflections exceeded the threshold value despite the presence of a thorax side air bag. The peak deflection was measured on the lower thoracic rib for all tests including the FMVSS No. 214 test. This lower thoracic rib appeared to be adjacent to the arm rest on the door. The HIC36 measurements were all remarkably low, especially considering the proximity of the dummys head to the hood of the striking vehicles, as shown in Figure 25. The low HIC measures appear to demonstrate the protective performance of the Accord side curtain air bag. The peak abdominal forces generally increase with the mass of the striking vehicle. The injury measures generated by the SUVs and pickups all exceed those in the FMVSS No. 214 configuration. Only the rib deflection measurements would have affected the overall test performance.

Table 12. Side impact Honda Accord driver injury measures

Test	Striking Vehicle	HIC 36	Rib Def	Lower Spine	Abdom. Force	Pubic Force
4862	**214 MDB**	223.4	22.7	50.3	809.7	2405
5146	Venture	128.1	45.5	48.0	597.0	3361
5142	Caravan	68.5	37.0	36.0	622.8	2063
5151	Explorer	249.5	43.5	52.2	987.1	3804
5156	Trailblazer	281.0	45.4	60.0	974.8	4986
5141	Tundra	341.2	47.5	51.5	1404.8	3204
5161	Ram 1500	267.0	45.7	54.4	1343.8	3357

Figure 26 plots the normalized injury measures for the higher / stiffer vehicles against the lower / softer vehicle in the same category. The data points largely lie below the 45 degree line indicating that the crash outcome was worse for the vehicle struck by the lower / softer bullet vehicle. This is in direct opposition with NHTSA's previous fleet correlation [2]. However, the fleet correlation was based on fleet crash data almost completely without side curtain air bags. It appears that head protection provided by side curtain air bags may be a good countermeasure for the head injuries resulting from crashes similar to these.

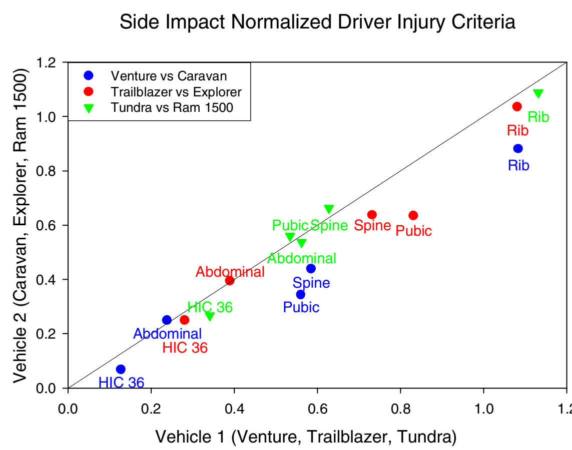

Figure 26. Normalized injury measures for the side impact vehicle pairs

The rear passenger injury measures were generally low as shown in Table 13. This table includes the injury measures from a FMVSS No. 214 configuration test with a SID2s rear occupant. Only the SID-2S FRG struck by the Tundra exceeded any injury tolerance level. The HIC36 for this test was also very close to the tolerance limit. The minivans generated lower injury measures than in the FMVSS No. 214 configuration test. The SUV and pickup impacts produced increased HIC36 measurements. The lower spine and acetabulum measures bracketed the FMVSS No. 214 configuration results.

Table 13. Honda rear passenger injury measures

Test	Striking Vehicle	HIC 36	Lower Spine	Acetabulum Illiac Force
5044	214 MDB	300.1	52.1	3777.9
5146	Venture	288.6	50.0	3565.6
5142	Caravan	283.5	42.5	2727.6
5151	Explorer	568.2	64.2	4038.2
5156	Trailblazer	452.4	63.2	4063.8

5141	Tundra	967.6	114.8	2901.3
5161	Ram 1500	598.7	50.6	3444.3

DISCUSSION

This test program was established to investigate the statistical correlation between vehicle performance measures and struck driver fatality. For all twelve of the frontal tests, only one of the drivers demonstrated a significant risk for serious injury. This driver was struck by the pickup vehicle with the lower performance measures. For the side impact tests, all but one of the struck drivers had a significant risk for serious injury. The one driver with the lower risk of thoracic injury, was struck by the minivan with the higher AHOF and lower stiffness. Neither of these observations support a correlation with the real world crash statistics. There are several factors confounding the conclusions of this test series. Kahane's analysis used data for model year 1991 through 1999 vehicles, this test series evaluated newer vehicles and the results may reflect the improved safety performance. The recent analysis by Austin [13] utilized different data sources and some newer vehicles, yet still found a correlation between AHOF risk of injury in side impact crashes. This test series along with the fleet analysis emphasize the complexity of predicting how vehicle designs will interact with other vehicles, their restraint systems, and the safety outcome for passengers of current and future vehicles.

This high resolution barrier test series unexpectedly brought into question the completeness of the load cell measurements collected using NHTSA's existing load cell barriers, particularly for the larger vehicles in this series. There was a substantial force measured above the older 4 by 9 load cell barriers. Almost all of the compatibility performance measures increased when the vehicles were tested on the taller high resolution barrier. The NHTSA load cell barriers were designed and built twenty years ago with smaller vehicles in mind. There is a need to update the crash walls used in NHTSA testing. Because the bullet vehicles were selected using incorrect compatibility metrics, the difference in the AHOF and stiffness measures were not as significant as originally intended.

NHTSA has already initiated repeatability testing to evaluate the 125 mm load cell barrier measurements. Preliminary test results indicate that the AHOF and stiffness measures can have acceptable repeatability. However, it is important to measure and correct for any vertical impact misalignment.

The test series also indicated concerns regarding the acceptance criteria used to review the historical NCAP data. Previously, test data were accepted if the force and accelerometer measurements closely correlated each other. The results of the Explorer NCAP test indicate that the acceptance criteria need to impose stricter requirements on the transfer function between the barrier force input and the accelerometer measured response. Research is underway to quantify appropriate acceptance criteria and to reevaluate the historic NCAP data.

The AHOF was developed as a performance measure because it is a simple method to distill the time varying load cell measurements down to a single number that is easily related to the vehicle design. The AHOF generally aligns with the primary energy absorbing structure of the vehicle. Furthermore, large differences in AHOF generally leads to frontal-frontal crash override behavior as shown in Figure 17. However, this test series and others [12] have shown that override does not always relate to a reduced safety outcome for the driver of the vehicle with the lower AHOF. These results seem to show that for lower speed vehicle-to-vehicle crashes, some override can improve occupant safety by providing a slower decceleration; however, at higher impact speeds this can lead to occupant compartment intrusion.

For side impact crashes, the safety correlation with the AHOF difference seems to have been reduced, if not removed, by the presence of side curtain air bags. While not a suprising conclusion, vehicle compatibility is most readily evaluated from real world crash statistics, yet the historical trends may not always apply to future vehicles. For front-to-front crashes manufacturers are introducing secondary energy absorbing structures designed to better interact with passenger cars. It may take several years to aquire enough crash data to see if these vehicle designs perform as intended.

Numerous methods have been used to evaluate vehicle stiffness and its potential contribution to vehicle compatibilty. Stiffness is an intuitively significant measure, that is hard to quantify in a rigorous manner. In a recent NHTSA study [11], the initial stiffness estimate was the only one of several stiffness estimates to show any real world correlation. However, this measure was developed from evaluation of NCAP barrier data and has not been rigorously linked to real world crash mechanisms. More research is needed to better understand the role of stiffness in vehicle-to-vehicle crashes and to improve the consistency and relevance of these measures.

Crash severity plays a significant role in the evaluation of vehicle compatibility. NHTSA's fleet correlations evaluate the probability of driver fatality, yet these test results generally indicate a low probability of serious injury. It is questionable whether this test series, particularly the offset tests, evaluated the same crash severity that was responsible for the fleet correlations. It is also likely that the safety performance of the target vehicle's restraint systems were improved from the restraint systems that led to previous fleet correlations.

None of the three test series provided significant insight or understanding to explain the fleet correlations with AHOF and stiffness metrics. The bullet vehicles did not have the distribution of AHOF and stiffness measures that was expected when the vehicles pairs were selected. The restraint systems in the target vehicle appear to have performed very well and likely reduced any effects to the varying compatibility of the bullet vehicle pairs. The side curtain air bags appear to have greatly reduced the potential for head injury in the side impact tests. While this test series does not help to explain the observed fleet safety correlations with the proposed compatibility measures, it does provide significant insight into the complex safety interactions and mechanics of vehicle crash compatibility.

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EEVC Approach to the Improvement of Crash Compatibility between Passenger Cars

Eberhard Faerber
Bundesanstalt für Strassenwesen (BASt)
Federal Highway Research Institute, Germany
on behalf of EEVC WG 15
Paper Number: 05-0155

ABSTRACT

The objective of European Enhanced Vehicle-safety Committee (EEVC) Working Group (WG) 15 *Car Crash Compatibility and Frontal Impact* is to develop a test procedure(s) with associated performance criteria and limits for car frontal impact compatibility. This work should lead to improved car to car frontal compatibility and self protection without decreasing the safety in other impact configuration such as impacts with car sides, trucks, and pedestrians.

The group consists of national government representatives who are supported by industrial advisers. The Working Group serves as a focal point for European research conducted by national and industry sponsored projects. The working group is responsible for collating the results from this research to achieve its objectives. EEVC WG 15 serves as a steering group for the car-to-car activities in the "Improvement of Vehicle Crash Compatibility through the development of Crash Test Procedures" (VC-COMPAT) project partly funded by the European Commission.

This paper presents a review of the current European research status. It also identifies current issues with candidate test procedures and lists the parameters that should be considered in assessing compatibility. The current candidate test procedures are:

- an offset barrier test with the progressive deformable barrier (PDB) face
- a full width wall test with or without a deformable aluminium honeycomb face and a high resolution load cell wall
- an offset barrier test with the EEVC barrier and load cell wall.

These candidate test procedures must allow assessment of structural interaction, frontal force levels and compartment strength.

The Working Group will report its findings to the EEVC Steering Committee and propose a test procedure in November 2006.

INTRODUCTION

Since the 2003 ESV-Conference[1] the *Terms of Reference* of Working Group 15 have been revised. The new *Terms of Reference* are to:

- develop a test procedure to assess car frontal impact compatibility. Work will concentrate on car to car frontal compatibility whilst also considering the effects on other accidents such as impacts with the side of cars, trucks , pedestrians and roadside obstacles;
- establish criteria to rate frontal impact compatibility;
- identify potential benefits from improved frontal impact compatibility;
- through continued research of frontal impact protection, ensure that steps to improve frontal impact compatibility will also lead to improved front impact protection;
- co-ordinate the EEVC contributions to the IHRA working group on Compatibility and Advanced Frontal Impact.

From March 2003 to February 2006, WG 15's research activities are focused on the VC- COMPAT t project [2]. The VC-COMPAT project is partly funded by the European Commission and the contributions of national governments. The main aim of WG 15 and the VC-COMPAT project is to develop a test procedure or a set of test procedures to improve the compatibility of car structures in frontal impacts without decreasing the safety in other impact configuration such as impacts with car sides, trucks, and pedestrians. The VC-COMPAT project consists of two legs: a car to car leg and a car to truck leg. For the car to car leg, EEVC WG 15 serves as a steering group. This means that there is a close co-operation between the VC-COMPAT consortium and WG 15. Research results developed in VC-COMPAT are analysed and discussed in WG 15. Proposals for special test parameters, analysis methods, and the selection of car models to be tested are made by WG 15 and forwarded to the VC-C COMPAT consortium.

OBJECTIVES EEVC WG 15

WG 15 discusses compatibility issues and evaluates its objectives in terms of a route map. The listed objectives represent the current opinions of the group.

General

- Proposed test procedures must address both partner and self protection in frontal impacts without decreasing current (regulatory) self protection levels in other impacts, in particular frontal and side impact.
- The number of additional test procedures should be kept to a minimum.
- Test procedures should be internationally harmonised.

Short Term (aim to report suitable test procedures to EEVC steering Nov 2006)

- Improve structural interaction between vehicles
- Control new requirements for passive safety (regulatory and rating) to ensure that frontal force mismatch does not become greater than current self protection force levels in particular to stop the increase of frontal force level of heavy vehicles.
- Control new requirements for passive safety (regulatory and rating) to ensure that compartment strength does not become less than current levels, especially for light vehicles

Medium Term (Aim to report suitable test procedures to EEVC steering Nov 2010?)

- Improve compartment strength, especially for light vehicles
- First steps to improve frontal force matching
- Further improve structural interaction.

(Status January 31, 2005)

CURRENT ACTIVITIES

As already stated in the previous paper of EEVC WG 15 [1], the ideal behaviour of the car front end (such as in a car to barrier test) can not be seen in all car to car tests. Poor structural interaction is still present in current car to car crashes which results in compartment intrusion in one or both of the cars involved, even at substantially lower test speeds than in regulatory or Euro NCAP testing. The main problem during the crash is that the front-end structures may not stay aligned and do not deform as ideally as designed. This is strongly linked to overriding/ under riding phenomena. It is thus important to ensure the controlled interaction of the vehicle structures involved car during the crash.

As already mentioned the main objective of the VC COMPAT project is the further development of the existing proposals for a potential compatibility test procedure or set of test procedures to be applied in test requirements. To understand the problems highlighted above, the VC-COMPAT project is divided into the following research activities:

- **A structural survey** to create a database of positions and dimensions of the important energy absorbing structures in vehicles. This will be used to determine appropriate structural interaction areas for vehicles.
- **Accident analysis** to estimate the benefit and cost of improved compatibility.
- **A crash testing program** of car-to-car and car-to-barrier crash tests to validate the crash test procedures and develop appropriate performance criteria.
- **Mathematical modelling** to support the development of the test procedures and the cost benefit analysis.

In addition to the co-ordinated activities in VC-COMPAT, EEVC-WG15 is also an exchange point where the results of industry research projects and ongoing national projects are shared. The joint research of the European manufacturers, organised by ACEA has been evaluating the test procedures under review by EEVC WG15. Recent crash test results from ACEA sponsored tests have been shared with EEVC WG15.

COMPARISON OF TEST PROCEDURES

Details of the potential test candidates under consideration by EEVC WG15 have been presented by their developers[3][4]. These test procedures are still under further consideration and consist of:

1. Full width Deformable Barrier (FWDB) test at 56 km/h to assess structural interaction.
2. Progressive Deformable Barrier (PDB) test at 60 km/h to assess structural interaction and frontal force levels.
3. Offset Deformable Barrier (ODB) test at 64 km/h to assess frontal force levels.
4. High speed Offset Deformable Barrier (ODB) test at 80 km/h to assess compartment strength.

For the FWDB test[3] the honeycomb barrier consists of two layers. The front layer has a low stiffness to generate shear forces for the front end structures. The rear layer with a higher stiffness is segmented (according to the load cell wall array) to separate the main load structures of the car and detect them on the load cells without bridging effects. The assessment of compatibility is based on homogeneity criteria for horizontal rows and vertical columns taking also into consideration the average height of force (AHOF). A recently developed relative homogeneity criterion is under consideration to overcome the mass dependency of the assessment. The ground clearance of the load cell wall and the honeycomb barrier has been adjusted to 80mm from the previous value of 50mm. This adaptation is to center two rows of load cells in the FMVSS Part 581 zone.

For the PDB test[4] the barrier stiffness increases with depth and has upper and lower load levels to represent an actual car structure. This setup is designed to create shear forces on the vertical and lateral connections of the front structures of the test object. The test procedure is aimed at both self and partner protection. The current assessment for compatibility is based on three assessment criteria: the partner protection assessment deformation (PPAD), the average height of deformation (AHOD) and the average depth of deformation (ADOD). All of these criteria are based on the deformation measurements from the barrier face.

The ODB test procedure with an overlap of 40%, the standard ECE R. 94 test, is modified with the addition of a high resolution load cell wall behind the deformable element. The increased test speed of 64 km/h (from the R94 56 km/h) is currently used in Euro NCAP and some of the previous test experience is available in the group.

The high speed ODB (80 km/h) test uses the same test configuration as the 64 km/h ODB. It aims to ensure that a car's compartment strength exceeds a minimum requirement so that it is able to withstand the forces imposed by another car. Note that no instrumented dummy measurements are taken in this test.

To assess the different test procedures envisaged by WG 15, the following parameter list was developed to assist the decision process.

Parameters to be Considered in Assessing Compatibility (status May 2004)

1. Structural interaction

1.1 Reproduction of frontal car to car accident loading
1.2 Show vertical force force/deformation distribution of the car front
1.3 Show horizontal force/deformation distribution of the car front
1.4 Show time history of local forces/deformations
1.5 Potential to show strength of lateral connections between load paths
1.6 Potential to show strength of vertical connections between horizontal load paths

2. Reproduction of Collapse Modes of Load Paths

2.1 Reproduction of frontal car to car accident collapse modes
2.2 Show time history of total forces
2.3 Potential to show optimum energy absorption of car front structures
2.4 Compartment strength to maintain compartment integrity
2.5 Potential to measure compartment strength
2.6 Potential to evaluate compartment integrity

3. Test Procedure

3.1 Simplicity of test procedure
3.2 Repeatability/reproducibility of test procedure

4. Others

4.1 Potential to harmonise with existing legal test procedures for frontal impact
4.2 Applicability to all vehicle types
4.3 Availability of objective assessment criteria.

POSSIBLE SET OF TEST PROCEDURES

The EU-Commission project, APROSYS, has recently started. This project includes an investigation of frontal impacts and potential necessity of a restraint system test in Europe. Therefore a full width test with a high deceleration pulse is under investigation in this project. The applicability of the THOR dummy for this test is also included in the project. The EEVC Working Group 15 is acting as an observer and advisor.

In EEVC WG 15 the opinion is growing that a set of two test procedures may be the best approach to improve self and partner protection in car frontal impacts. EEVC WG 16, which was merged with WG 15 two years ago, had proposed in its final report to introduce a full width test to current legal frontal impact testing. The standard ODB test sets high structural resistance requirements to the tested car while the full width test would complement the ODB test requirements with a high deceleration restraint system test.

WORLDWIDE HARMONISATION PROSPECTIVE

The EEVC WG15 has discussed the request from IHRA to consider the use of a full width test in the US, with or without a deformable face, using a load cell wall to measure the average height of force as a first step for the assessment of car to car compatibility. The working group agrees that the full width test can be used to measure the height of force and that controlling this could be a useful first step for improving SUV/ LTV compatibility with cars. However, the WG15 does not consider the control the average height of force as a sufficient instrument to measure compatibility. Adding a deformable face would provide further development. In addition to improving the measurement of force height, a deformable face would facilitate the future measurement of an interaction "footprint". The use of this interaction footprint would be even more important when the application is extended to conventional cars.

The progress of the IHRA Compatibility and Frontal Impact Group is reported in a separate presentation. From the WG 15 side there is some concern to find a world wide agreed test since there are substantial differences among the U.S., Europe, and Japan car fleets.

CONCLUSIONS

In EEVC WG 15 the opinion is growing that two test procedures could improve car self protection as well as car to car compatibility and could complement each other:

- an offset deformable barrier test procedure with a progressive deformable element seems to have a higher potential for defining compatibility assessment criteria than the current ECE R. 94 element
- a full width barrier test with a full width deformable element and high resolution force measurement behind the deformable element.

In close a co-operation between the VC-COMPAT consortium and EEVC WG 15, the project results will be evaluated carefully and objectively. It seems not too unrealistic to expect that end of 2006 EEVC WG 15 will in the position to propose a test procedure or a set of test procedures to assess the frontal compatibility between cars

Membership of EEVC WG 15

Official Members:

Eberhard Faerber, BASt, Germany, *chairman*
Pierre Castaing, UTAC, France, *technical secretary*
Pascal Delannoy, Teuchos-Snecma Group, France
Giancarlo Della Valle, Elasis, Italy
Dr. Mervyn Edwards, TRL, United Kingdom
Joaquim Huguet, IDIADA, Spain
Dr. Robert Thomson, Chalmers University of Technology, Sweden
Cor van der Zweep, TNO, The Netherlands

Industry Advisors:

Domenico Galeazzi, FIAT, Italy
Anders Kling, Volvo Car Corporation, Sweden
Robert Zeitouni, PSA Peugeot Citroen, France
Dr. Robert Zobel, Volkswagen AG, Germany

Observers:

Stephen Summers, NHTSA, USA

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JAPAN RESEARCH ON COMPATIBILITY IMPROVEMENT AND TEST PROCEDURES

Koji Mizuno
Nagoya University
Kunio Yamazaki
Yuji Arai
Japan Automobile Research Institute
Masao Notsu
Ministry of Land, Infrastructure and Transport (MLIT)
Japan
Paper Number 05-0185

ABSTRACT

This paper summarizes the compatibility research project conducted by JMLIT. Test procedures to assess vehicle compatibility were investigated based on a series of crash tests. In the IHRA (International Harmonized Research Activities) Compatibility Working Group, the full-width tests have been agreed upon for structural interaction evaluation of the Phase 1 approach. Thus, the JMLIT compatibility research project mainly focused on this test procedure.

Full-width rigid and deformable barrier tests were compared with respect to force distributions, vehicle deformation and dummy responses. In full-width deformable barrier tests, shear deformations are excited, and forces from structures can be clearly shown in barrier force distributions. The average height of force (AHOF) determined in full-width rigid and deformable barrier tests was similar. Basically, the full-width deformable barrier tests can be used as high acceleration tests. The dummy injury criteria were also similar between full-width rigid and deformable barrier tests, although for small cars the injury criteria can be inferior for full-width deformable barrier test due to sensor delay.

In order to investigate SEAS detection in the barrier force distributions, full-width tests were conducted for SUVs (sport utility vehicles) with and without SEAS. The reaction force of the SEAS could be detected in the full-width deformable barrier test. The VNT (vertical component of negative deviation from target row load) will be a useful criterion to evaluate the SEAS reaction force.

Car-to-car crash tests were conducted, and the compartment deformations of a small car in a crash into a medium car, MPV and SUV were compared. The structural interaction was poor in the SUV collision, and the passenger compartment of small car collapsed. Even structural interaction was good, a relatively large intrusion of the small car occurred in an MPV (multi-purpose vehicle) crash. Force matching and compartment strength will be significant for the next phase of compatibility improvement.

INTRODUCTION

Compatibility is defined as the ability to protect not only the occupants, but also other road users as well. Analyses of global accident data of car-to-car collisions from various countries have indicated that there are vehicles with low compatibility, such as cars with poor self-protection and cars with high aggressivity with respect to other cars. The aggressivity of SUVs has become an issue in the United States and to a lesser extent, Australia, as has the self-protection of small cars in Europe. In Japan as well, vehicle sizes vary widely, and compatibility is considered an important problem. It is therefore necessary to evaluate and improve compatibility performance based on crash tests.

Test procedures for evaluating and improving the compatibility of passenger cars are currently under discussion in the IHRA Compatibility Working Group [1]. Japan considers the activities of the IHRA to be a significant way to inform future legislation and regulation, and has conducted research with the aim of making an active contribution to these activities. The proposed IHRA phase 1 approach used a full-width test [1]. In the proposal, barrier force distributions are measured and evaluated to improve structural interaction. To have enough resistance force in the common interaction zone to avoid structural misalignment of SUV is considered as short term as phase 1a.

This paper summarizes the results of crash tests that Japan has conducted and reported to the IHRA Compatibility Working Group from 2003 to 2005. In the tests, the full-width rigid barrier (FWRB) test and full-width deformable barrier (FWDB) tests were compared with respect to barrier force distributions, vehicle deformations, vehicle accelerations, injury readings and SEAS detection. This study also includes the analysis of Australia PDB test to investigate the compartment strength. Car-to-car crash test series of small cars was examined, and the compartment intrusion was compared with respect to the structural interaction and compartment strength.

LOAD CELL WALL IN FULL-WIDTH TESTS

In full frontal tests, the barrier force distributions are measured from load cells, and structure alignment and homogeneity which are effective for structural interactions, are evaluated. Since Japan has a full-width rigid barrier crash test requirement in the regulation, it will be useful if the compatibility can be evaluated in this test configuration. In the present study, force distributions in full-width rigid and deformable barrier crash tests were examined from the data of JMLIT compatibility project and JNCAP (Japan New Car Assessment Program) tests.

Figure 1 shows the load cell alignment of IHRA agreement [1] and of JMLIT test series at a JARI test facility. The common interaction zone in IHRA is at row 3 and 4, which is from 330 mm to 580 mm above ground level. At JARI, the ground clearance of the load cell wall is 125 mm, and the area of rows 2, 3 and 4 correspond to rows 3 and 4 in the IHRA agreement load cell alignments.

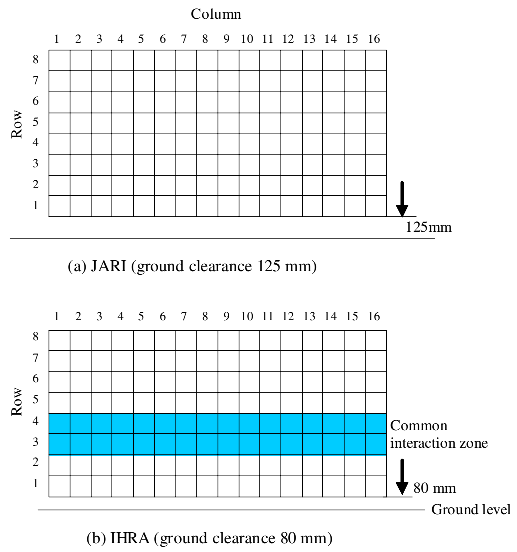


Figure 1. Alignment of load cell wall in JARI test facility and in IHRA agreement.

FULL-WIDTH DEFORMABLE BARRIER TESTS

Full-width deformable barrier tests were carried out for five vehicles using a deformable element developed by the Transport Research Laboratory (TRL) [1][2]. The first layer of the deformable element has a crush strength of 0.34 MPa with 150 mm depth, and the second layer has a crush strength of 1.71 MPa with 150 mm depth. Test vehicles include the minicar, small car, medium car, small SUV, MPV, and SUV that have different load paths (Table 1). Hybrid III dummies were used in driver and front passenger seats. An impact velocity was 55 km/h.

Table 1.
Test matrix of full-width deformable barrier tests.

Test car model	Vehicle class	Load path	Kerb mass (kg)	Test mass (kg)
Suzuki Wagon R	Minicar	Single (w/o bumper beam)	840	1041
Toyota Vitz (Yaris)	Small car	Single	921	1091
Subaru Legacy	Medium Car	Single (stiff lower Cross member)	1510	1699
Subaru Forester	Small SUV	2-stage (subframe)	1443	1638
Honda Stepwgn	MPV	Single (stiff lower Cross member)	1530	1717
Toyota Surf	SUV	Single (frame-type, SEAS)	1878	2076

Test vehicles after tests are presented in Figure 2. Generally, it was observed that the deformable element excites shear deformation of structures in the full-width deformable tests, which is similar in car-to-car crashes. The lower cross members and SEAS deformed rearward. Thus, the forces of the lower cross member which can prevent underride will be assessed effectively in the full-width deformable barrier tests.

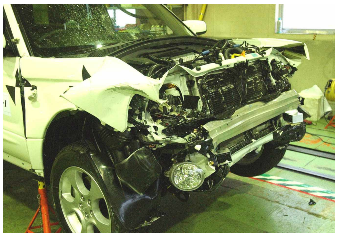
As shown in Figure 2, the deformation of bumper rearward bending was observed in full-width deformable barrier tests, which is a different deformation mode in full-width rigid barrier crash tests. In a Legacy, according to the rearward bending of stiff bumper beam, the front-ends of longitudinal members bent and wrapped inside at the point where the cross-section area changes. Sensors attached to the front end of longitudinal members also may not work as designed when the longitudinal member deforms in this way. This inward deformation of longitudinal members was observed more or less for all tested vehicles, except the Wagon R, which does not have a bumper beam, and the thin longitudinal members penetrated the honeycomb.

Distributions of each load cell peak force are presented in Figure 3. The engine impact forces are mitigated by the deformable barrier, and forces of structures in a longitudinal direction can be seen clearly. Especially for Surf or Stepwgn, the longitudinal members are so stiff that they bottomed out the barrier, and the barrier force from these structures became high. The Forester has a subframe, Surf has a SEAS, and Stepwgn has a stiff lower cross member. If these lateral structures are stiff enough, they push the honeycomb and transfer forces at the barrier, though the force levels from lateral structures are not so high.

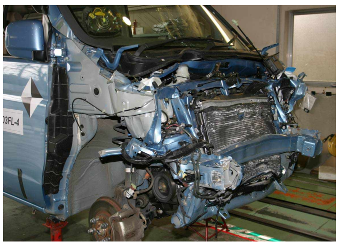
(a) Wagon R

(b) Vitz

(c) Legacy



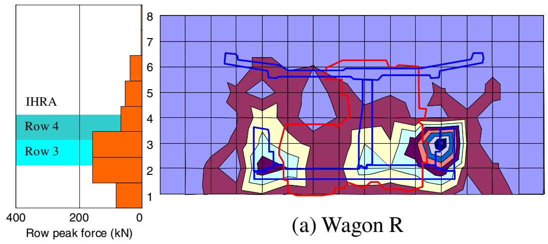
(d) Forester



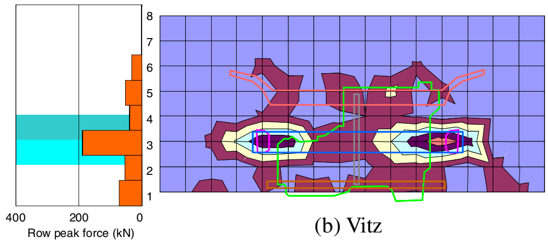
(e) Stepwgn

(f) Surf

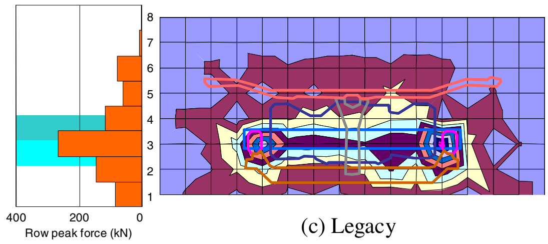
Figure 2. Vehicle deformation in full-width deformable barrier tests.



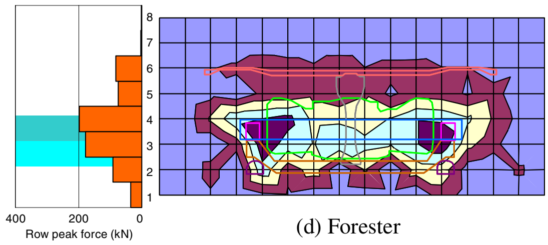
(a) Wagon R



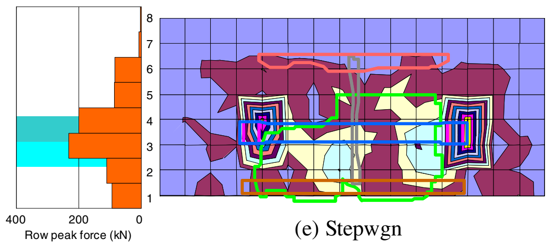
(b) Vitz



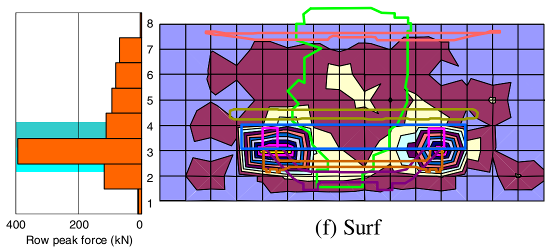
(c) Legacy



(d) Forester



(e) Stepwgn



(f) Surf

Figure 3. Peak cell force in full-width deformable barrier tests.

The VNT is the difference of row force from a minimum target row load, which was proposed by TRL [1]. The VNT is a criterion to evaluate the reaction force in common interaction zone. The VNT is calculated as:

$$VNT = \sum_{Row(i)=3}^{4} IF[\{R_i \le TR\} THEN, ABS(R_i - TR), \quad ELSE = 0]$$

where $R_i = \sum_{j=1}^{allcolumns} f_{ij}$,

f_{ij} = peak cell force.

The VNT will be an effective parameter to evaluate the resistance force in the common interaction zone if the target load level is selected properly. In the IHRA, the target row load is proposed as 100 kN. As shown in Figure 4, since the ground-height of the longitudinal member of Wagon R is low, the force level in row 4 became small. As the Vitz has a single load path, only force in row 4 is large. Though the VNT is a criterion of resistance force for SUV structural alignment, the row load of minicar and small car can be smaller than the target row load of 100 kN.

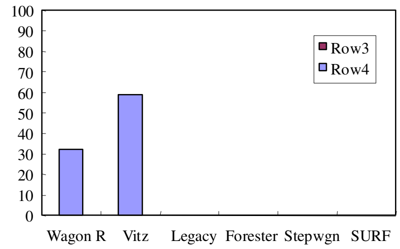
The HNT (horizontal component of negative deviation from target cell load) is also proposed by TRL as:

$$HNT = \sum_{Row(i)=3}^{4} \sum_{Column(j)=-2}^{+2} IF[\{f_{ij} \le TC_i\} THEN, \quad ABS(f_{ij} - TC_i), \; ELSE = 0]$$

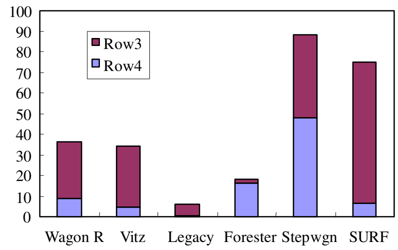
where TC_i is a target cell load calculated as:

$$TC_i = \frac{\sum_{j=1}^{allcolumns} f_{ij}}{(80\% \text{vehicle width})/(\text{load cell width})}.$$

The HNT is a parameter to evaluate the bumper beam stiffness. In Figure 4, the HNT of the tested vehicles is also shown. The HNT is good for Legacy and Forester which has a stiff bumper beam. The HNT is not good for other cars with a less-stiff bumper beam. The HNT is not also good for the SURF which has stiff longitudinal members. The HNT depends on the bumper beam stiffness as well as longitudinal member stiffness because TC_i heavily depends on the longitudinal member stiffness. Accordingly, it will be difficult to distinguish between the less-stiff bumper beam and the stiff longitudinal members on the basis of HNT. It might not be realistic to consider that an extremely stiff bumper beam is needed for vehicles with stiff longitudinal members. Further investigation will be needed for the HNT to evaluate the bumper beam stiffness.



(a) VNT



(b)HNT

Figure 4. VNT and HNT in full-width deformable barrier crash tests.

COMPARISON OF FULL-WIDTH RIGID AND DEFORMABLE BARRIER TESTS

Criteria of Structural Interaction

__AHOF__ The AHOF in full-width deformable and rigid barrier tests were compared and shown in Figure 5. The AHOF measured in both barriers have a strong correlation. The honeycomb may affect the pitching of vehicles on impact, which can lead to higher AHOF. The AHOF of the Stepwgn and Wagon R in full-width deformable barrier tests are lower than in full rigid barrier tests, because the upper structures of these vehicles do not contact the whole barrier due to the limited size of the deformable element.

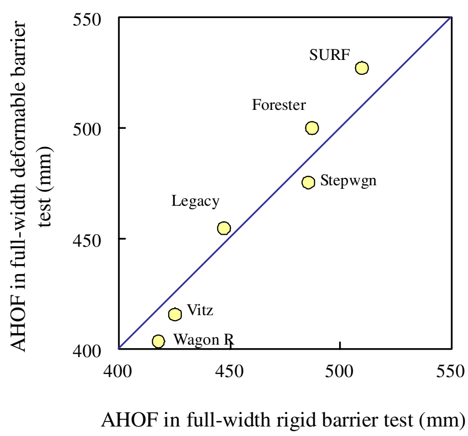
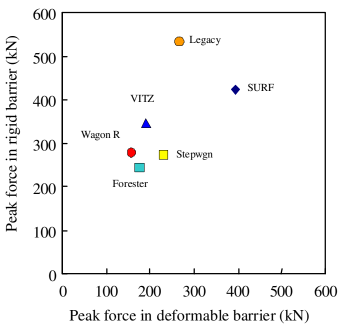


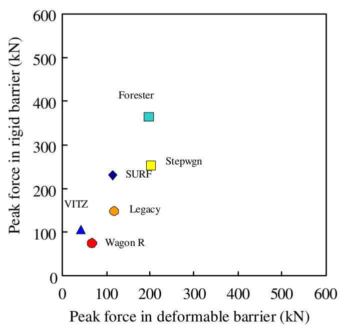
Figure 5. Average height of force in full-width rigid and deformable barrier tests.

Barrier Row Force Levels Estimated in Full Rigid Barrier Crash Tests In order to examine the target load level of 100 kN in full-width deformable barrier tests, the peak row load in the current vehicles was investigated using full-width rigid barrier test data. Figure 6 shows the sum of peak cell force in rows 3 and 4. As there is a correlation between the peak row load in full-width rigid and deformable barrier tests, the peak row loads in full-width rigid barrier tests were used for analysis. Figure 7 shows the sum of peak force in all load cells. The total peak cell forces in full-width rigid and deformable barrier tests have a linear relation, and the slope is 1.3. Therefore, the target row load of 100 kN in full-width deformable barrier tests will correspond to 130 kN in full-width rigid barrier tests.

Figure 8 shows the peak row force of minicars, small cars, medium and large cars, MPV and SUV in full-width rigid barrier crash tests. Due to low ground-height of longitudinal members, the peak force in rows 2 and 3 of some minicars is more than 130 kN whereas the peak force in row 4 is smaller than 130 kN. For many cars, the peak force in row 3 is higher than rows 2 and 4 because the longitudinal members contact row 3. This concentration of peak row force in row 3 will shift to rows 3 and 4 in the IHRA agreement load cell alignment since the longitudinal members will bridge between rows 3 and 4 in the IHRA alignment. However, some small cars and minicars will not satisfy the target row load of 100 kN in full-width deformable barrier tests.



(a) Row 3 peak force



(b) Row 4 peak force

Figure 6. Peak row forces in rows 3 and 4 in full-width rigid and deformable barrier crash tests.

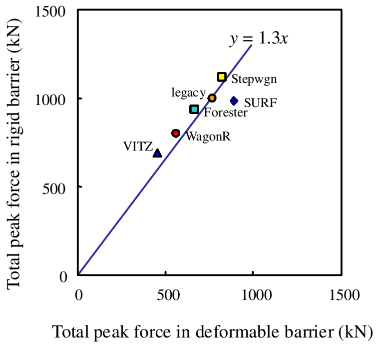
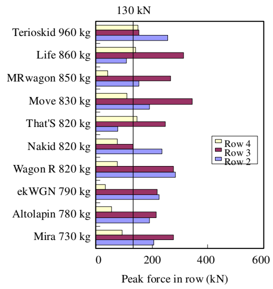
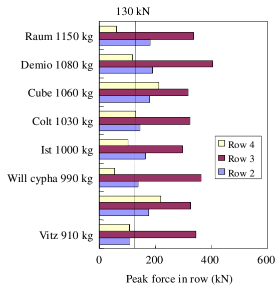


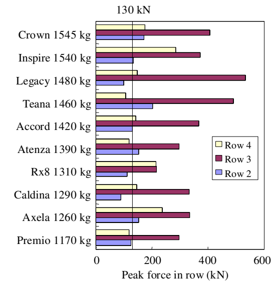
Figure 7. Total peak cell force in full-width rigid and deformable barrier crash tests.



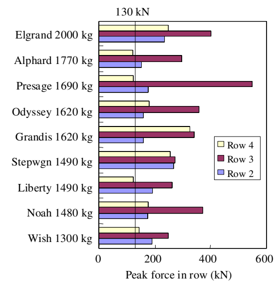
(a) Minicar



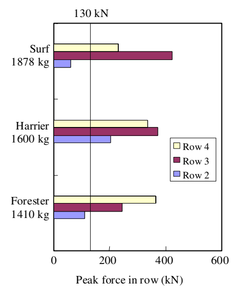
(b) Small car



(c) Medium & large car



(d) MPV



* Kerb mass is shown

(e) SUV

Figure 8. Peak cell force in row 2, 3 and 4 of vehicles in full-width rigid barrier crash tests.

Vehicle Acceleration and Dummy Responses

The dummy response and car acceleration of Wagon R are shown in Figure 9. The data also include the results of a car-to-car full frontal crash test with identical car models (Wagon R). The results of the full frontal car-to-car crash test are quite similar to those of full-width rigid barrier test. Because of a crash sensing time difference between rigid and deformable barrier tests, the dummy restraint start times were later in deformable barrier tests compared with rigid barrier test. In the full-width deformable barrier test, the chest acceleration delayed and there is no peak around 25 ms by the seat belt pretensioner. As a result, the interaction of seat belt and airbag with dummies differed in both tests. The rear-loaded crash pulse in the full-width deformable barrier test could also lead to higher injury criteria. The deformable barrier can cause relatively high injury criteria for small cars with high-deceleration.

Figure 10 shows injury criteria of the driver dummy in full-width rigid and deformable barrier tests. Dummy criteria were similar for full-width rigid and deformable barrier tests. For Wagon R, the injury criteria were relatively higher in the full-width deformable barrier test.

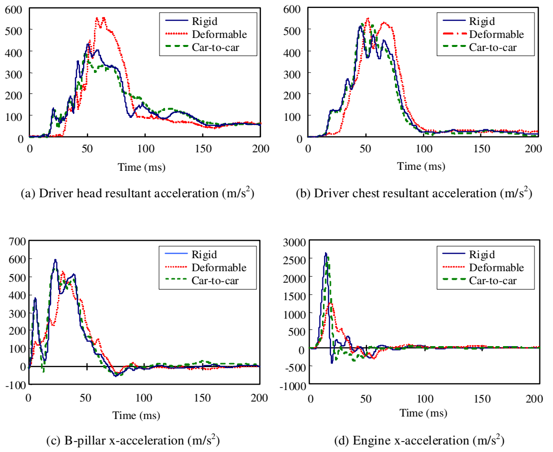


Figure 9. Dummy response and vehicle deceleration in full-width and deformble barrier tests.

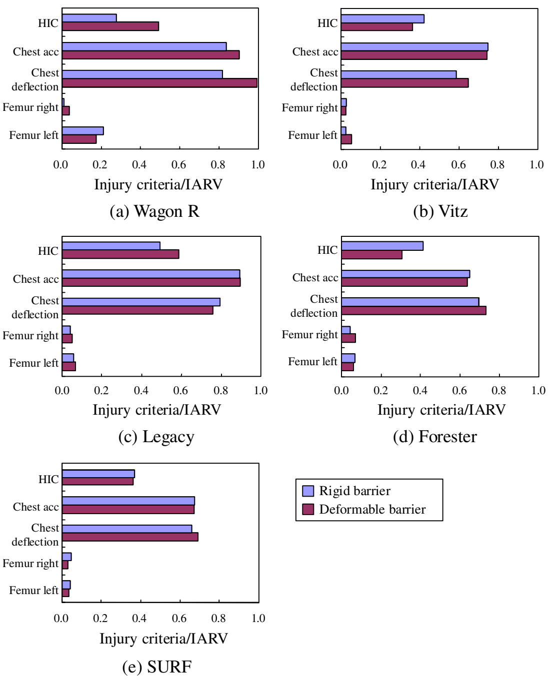


Figure 10. Dummy injury criteria in full-rigid and deformable barrier tests.

SEAS DETECTION IN FULL WIDTH DEFORMABLE BARRIER TESTS

Vehicle Deformation

In order to examine SEAS detection in force distributions in full-width tests, the force distributions of SUV with or without SEAS were examined. Test vehicles were an SUV (Toyota SURF) that has a frame-type longitudinal member with SEAS. The kerb mass of the vehicle is 1868 kg. Table 2 shows the test matrix. The results were compared to those of SURF with SEAS in full-width deformable and rigid barrier tests. The ground clearance of the load cell barrier was 125 mm. In this load cell alignment, the SEAS made contact with row 2 load cells. Thus, in this study, the VNT was calculated in rows 2, 3 and 4 though they are usually calculated in a common interaction zone (rows 3 and 4).

Figure 11 presents the SUV structure. The SEAS is mounted directly under the longitudinal member. From the front-edge of the bumper cover, the length of the bumper beam is 62 mm, and the SEAS is 377 mm in the longitudinal direction. In a case of SUV without SEAS, the SEAS were removed from the original SUV at the SEAS mount.

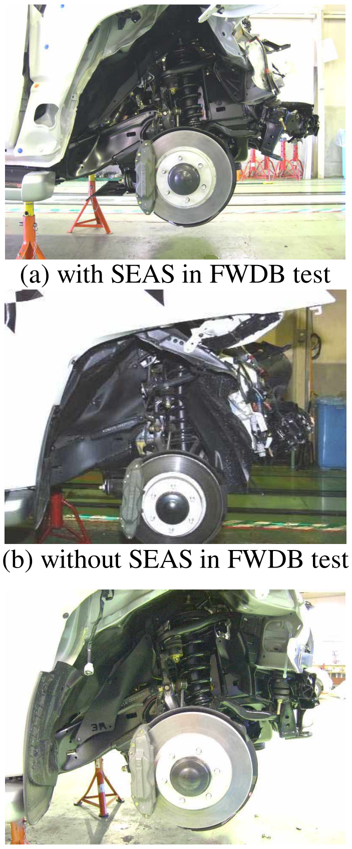
The vehicles after tests are shown in Figure 12. For the SUV with SEAS in the full-width deformable barrier test, the SEAS deformed rearward. In the full-width rigid barrier test, the SEAS did not deform rearward, and the SEAS made contact with the suspension cross member behind SEAS in accord with the collapse of longitudinal member. There were also differences in the deformation mode of longitudinal members. For the SUV with SEAS in the full-width deformable barrier test, the front-end of longitudinal members deformed downward in accord with to rearward bending of SEAS.

Figure 13 is a bottom view of the tested vehicle. For the SURF with SEAS, the deformation was symmetric between right- and left-hand longitudinal members. The front end of the longitudinal members deformed slightly inward (39.0 mm on the right-hand longitudinal member and 32.9 mm on the left-hand longitudinal member). On the other hand, for the SUV without SEAS, both longitudinal members deformed outward. The front end of the right-hand longitudinal member deformed 97.2 mm and the left-hand longitudinal member 15.1 mm because the longitudinal member became unstable due to removal of SEAS. As a result, they contacted a different location on the load cells from that of the original SUV with SEAS.

Table 2.
Test matrix of SUV in full-width tests to investigate SEAS detection.

Car model	Test	Impact velocity (km/h)	Test mass (kg)	Impact location from target
SURF with SEAS	FWDB	55	2076	20 mm (right side)
SURF without SEAS	FWDB	55	2076	7 mm (right side)
SURF with SEAS	FWRB	55	2076	18 mm (right side)

Figure 11. SEAS of SUV.

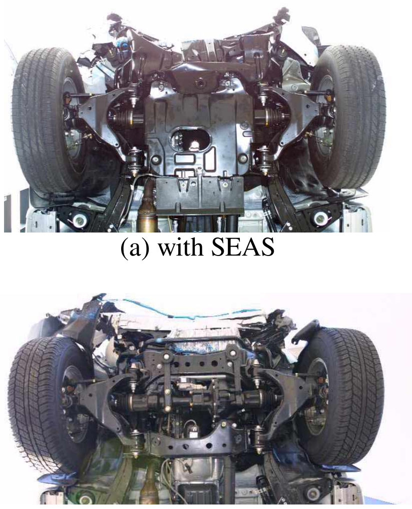


(a) with SEAS in FWDB test

(b) without SEAS in FWDB test

(c) with SEAS in FWRB test

Figure 12. Deformation of longitudinal member of SUV with and without SEAS in full-width deformable and rigid barrier test.



(a) with SEAS

(b) without SEAS

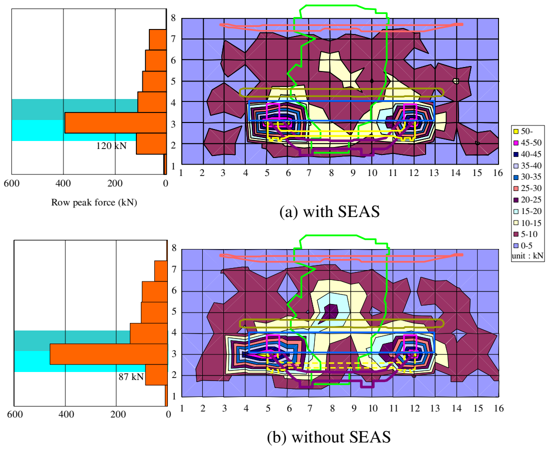
Figure 13. Bottom view of SUV with and without SEAS.

Peak Cell Force from SEAS

Peak cell force distributions of the SUV with and without SEAS are presented in Figures 14 and 15. There are smooth force distributions around the SEAS. In the row 2 where SEAS made contact, the row load was about 120 kN. On the other hand, in row 2 of SURF without SEAS, it was 87 kN. Thus, this test result supports the IHRA proposed threshold of 100 kN for target row load in the assessment area, which will be able to be achieved by attachment of the SEAS. The VNT of the SUV with SEAS is 0 kN for rows 2, 3 and 4. The VNT of the SUV without SEAS is 13, 0, 0 kN for rows 2, 3, and 4, respectively. Thus, the VNT can be a useful criterion to assess the reaction force of SEAS.

In the test of SURF with or without SEAS, lateral shifts from a target location were 20 mm and 7 mm in the test (see Table 2). As shown in Figure 15, the left-hand longitudinal member can also contact adjacent load cell with such a small shift in tests. For the SURF without SEAS, the longitudinal member became unstable with bending, and also contacted more than one load cells (rows 3, 4 and 5), which led to different force distribution around the longitudinal member.

Figure 16 presents the peak cell forces for the SUV with and without SEAS. Row 2 with columns from 6 to 12 are the load cells which are in alignment with the SEAS. From these two graphs, it may be still difficult to conclude that the forces of row 2 were generated from SEAS deformation. This is because there are many load cells with small forces in the force distribution where the vehicle makes contact.



(a) with SEAS

(b) without SEAS

Figure 14. Peak cell force distributions of SUV with and without SEAS in full-width deformable barrier tests.

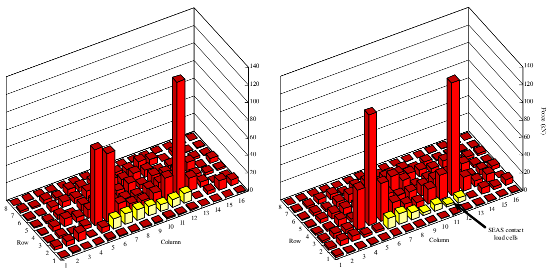
Row	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	Row Total	TCi
5	0.8	2.4	4.7	0.2	6.9	6.7	7.6	8.0	11.3	4.5	10.6	8.5	6.2	10.8	0.4	5.0	95	7.9
4	0.4	4.3	8.6	6.0	9.6	18.9	9.5 (0.1)	7.3 (2.2)	6.3 (3.3)	8.9 (0.6)	11.0	11.7	2.3	5.3	2.5	2.0	114	9.5
3	0.6	3.1	1.1	4.0	86.0	76.9	15.4 (13.6)	10.2 (18.8)	8.8 (20.2)	12.5 (16.5)	24.5	129	14.9	5.4	0.4	1.2	394	29.0
2	4.0	5.0	10.0	0.4	6.2	11.3	12.4 (0.0)	12.2 (0.0)	10.7 (0.0)	7.7 (2.3)	9.1	10.4	0.2	3.6	10.5	6.2	120	10.0

(a) with SEAS

Row	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	Row Total	TCi
5	0.7	4.3	6.6	7.1	6.0	8.6	4.4	23.7	14.8	3.6	6.5	3.2	2.5	8.7	2.8	0.8	104	8.7
4	1.7	2.0	7.5	3.5	14.0	16.3	17.0 (0.0)	10.8 (1.5)	10.2 (2.1)	12.1 (0.3)	14.9	16.2	7.8	4.0	5.9	4.6	148	12.4
3	2.5	5.1	5.1	45.2	125	42.6	16.5 (12.5)	9.1 (19.9)	6.5 (22.5)	16.7 (12.3)	27.4	127	15.4	6.1	8.9	0.4	460	29.0
2	2.4	6.1	6.4	2.6	2.7	11.4	12.2 (0.0)	8.3 (0.0)	3.3 (3.9)	6.8 (0.4)	2.5	5.3	0.4	6.8	3.2	6.4	86	7.2

(b) without SEAS

Figure 15. Peak cell force of SUV with and without SEAS to calculate VNT and HNT.



(a) with SEAS (b) without SEAS

Figure 16. Bar chart of peak cell force of SUV with and without SEAS in full-width deformable barrier tests.

The sum of the barrier force in row 2 where SEAS made contact was plotted against the vehicle displacement (Figure 17). The vehicle displacement was calculated from a double integral of the compartment acceleration. The force increases from the vehicle displacement of 0.4 m, where the SEAS began to contact the barrier. For the SUV without SEAS, the force level is small in the initial stage, and it increases after 0.5 m where lateral suspension structures start to contact the barrier. Consequently, it is considered that the barrier force in row 2 shows the SEAS reaction force in the full-width deformable barrier test. The result of SUV with SEAS in a full-with rigid barrier test is also shown in Figure 17. The force in row 2 does not increase until the deformation of 0.5 m. Since the vehicle deformation is flat in a rigid barrier test, the SEAS did not deform rearward and did not generate a reaction force against the barrier. Thus, it will be difficult to measure a SEAS reaction force in full-width rigid barrier crash tests.

The center of force (COF) was plotted with vehicle displacement (Figure 18). The COF is almost constant as the tested SUV which has a simple frame-type longitudinal member. The COF is smaller for the SUV with SEAS after the contact of SEAS. The average height of force (AHOF) was 527 mm for SUV with SEAS, and 552 mm without SEAS. There are several factors which can affect the AHOF such as engine impacts [3]. The criteria based on forces from row 2 such as VNT, may be a direct way to evaluate the SEAS reaction force compared to the AHOF.

The relative homogeneity assessment was calculated and shown in Figure 19. The homogeneity assessment was larger for the SUV with SEAS. Several factors can be considered for this reason. One is that the SUV longitudinal member was instable without SEAS, and contacted different load cells from the original SUV with SEAS. For SUV without SEAS, the impact forces of the engine became great due to bending of the left-hand longitudinal member, which also reduced the homogeneity assessment. Consequently, the load cell contact locations can significantly affect the barrier force distributions and homogeneity assessment. The influence of SEAS reaction force can be seen only for the homogeneity assessment in row which can be an override/underride criteria. Further investigation will be needed for the homogeneity assessment.

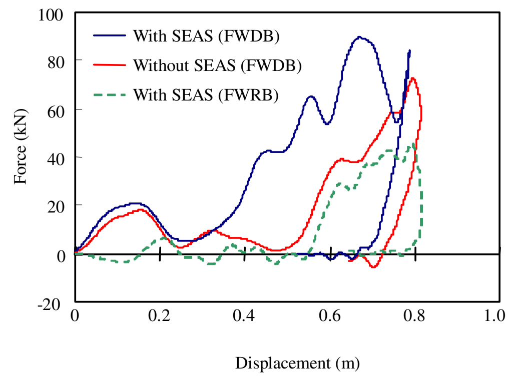


Figure 17. Barrier force in row 2 vs. vehicle displacement for SUV with and without SEAS in full-width deformable and rigid barrier tests.

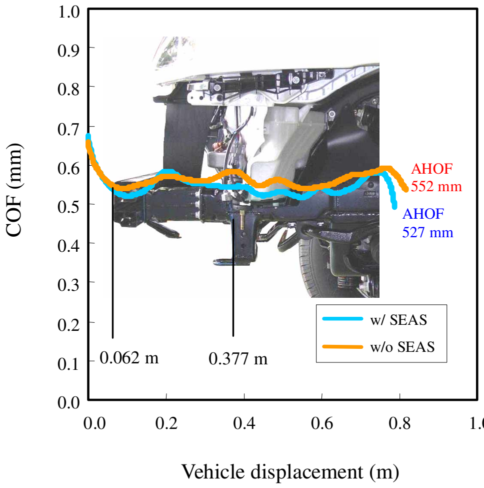


Figure 18. COF with vehicle displacement in full-width deformable barrier tests of SUV.

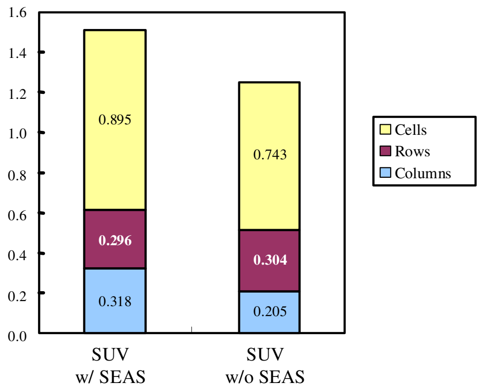


Figure 19. Relative homogeneity assessment in full-width deformable barrier tests of SUV.

EVALUATION OF COMPARTMENT STRENGTH IN PDB TESTS

Using Australian government data, the barrier forces in PDB tests were examined with respect to the compartment strength. The Australian government conducted PDB (progressive deformable barrier) offset tests using the Toyota Vitz (Echo or Yaris) at 60 and 74 km/h, and Vitz II at 74 km/h [4]. The Vitz has a simple structure with a single load path with two longitudinal members and a bumper beam. The Vitz II is a Vitz with a minor change, and the passenger compartment was strengthened from Vitz, whereas the front structures remain the same. The test data were provided by the Australian government.

The force-time histories of three tests are shown in Figure 20. In general, the barrier forces are similar in three tests although the Vitz passenger compartment collapsed in the 74 km/h test. The maximum force is the highest for the test at the lowest impact velocity of 60 km/h. The passenger compartment strength was evaluated based on criteria [5] (Figure 21). In the present study, the end of crash force is defined as the barrier force at the time when the engine acceleration is minimum after the engine makes contact with a firewall. However, it is rather difficult to determine the end of crash force in an objective way because the engine does not bottom out the barrier and engine acceleration is small during engine intrusion into the passenger compartment. The rebound force is a barrier force when the car separates from the barrier, and is determined from force-displacement curves. From the rebound force, the compartment strength is higher for the Vitz II than for the Vitz, which is a reasonable result. However, the rebound force is smaller for the Echo at 60 km/h than that at 74 km/h, even though the rebound forces are similar between 64 km/h and 80 km/h in tests using the EEVC barrier.

Because the PDB is deep and does not bottom out for cars, the barrier force may be difficult to use as criteria for compartment strength evaluation in an objective way. This situation is different from overload 80 km/h or ODB (offset deformable barrier) 64 km/h tests where the EEVC barrier bottoms out and the compartment resistance force can be transferred directly to the barrier force. According to PDB tests of the Vitz and Vitz II, the vehicle deformation mode is more similar to that in car-to-car crash tests compared to ODB tests. Thus, in PDB tests, the intrusion into the passenger compartment may be a reliable criterion for compartment strength evaluation.

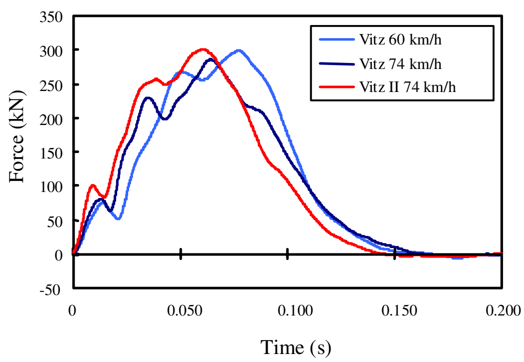


Figure 20. Barrier force-time histories in PDB tests.

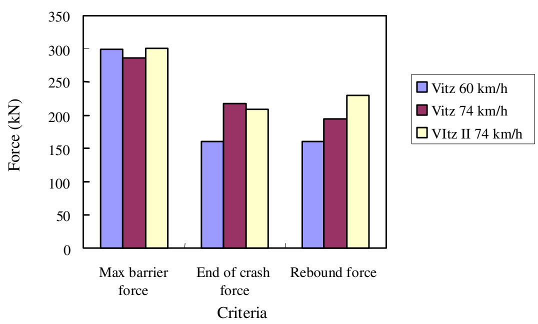


Figure 21. Passenger compartment strength criteria in PDB tests.

CAR-TO-CAR CRASHES

A series of car-to-car crash tests using a small car (Toyota Vitz) were conducted to investigate the structural interaction and compartment strength (Table 3). In the crash test series, the impact velocity was 50 km/h for both cars. The kerb mass of the Vitz is about 920 kg, and the test mass about 1090 kg. In Table 3, Vitz vs. Legacy crash test were conducted by the Australian government [4]. In order to examine the structural interaction, the SEAS was removed from the SURF.

Table 3.
Car-to-car crash test with Toyota Vitz. Impact velocity is 50 km/h.

Subject car	Other car			
	Model	Load path	Kerb mass (kg)	Test mass (kg)
Vitz	Legacy (Medium car)	1.5 Single (still lower cross member)	-	1600
Vitz II	Legacy (Medium car)	1.5 Single (still lower cross member)	1430	1589
Vitz II	Surf (SUV) w/o SEAS	Single Frame-type, SEAS was removed)	1906	2076
Vitz II	Odyssey (MPV)	2-stage (subframe)	1660	1830

Figures 22 and 23 show the deformation of Vitz. The crash test between the Vitz, Vitz II and Legacy demonstrated the effectiveness of passenger compartment strength. By stiffening the passenger compartment from Vitz to Vitz II, the A-pillar rearward displacement was reduced from 118 mm to 33 mm. The longitudinal member of Vitz made contact above the bumper beam of Legacy and deformed in upward direction. Therefore, the structural interaction was not still so good.

In a crash into a SURF which the SEAS was removed, the longitudinal member of SURF did not interact with the Vitz II longitudinal member, and it made contact the suspension strut, which induced a large intrusion into the passenger compartment of the Vitz II. The A-pillar rearward displacement of the Vitz was 349 mm. The right femur force of the driver dummy was more than the injury threshold (13.4 kN). If the SEAS was not removed from the original SURF, the SEAS could interact with a right-hand tire of the Vitz, and poor structural interaction would be improved.

In a crash into an Odyssey, the structural interaction was good, and the front structure of the Vitz absorbed the energy efficiently. However, due to the force mismatch between vehicles, the steering axis of the Vitz moved upward (100 mm), which led to high chest acceleration of the driver dummy (56.5G).

The crash test results demonstrate that after good structural interaction, there will not be a significant compartment collapse. However, there may be no end to control passenger compartment intrusion until the guidelines for force-matching and compartment strength are provided.

Vitz (vs. Legacy)

Vitz II (vs. Legacy)

Vitz II (vs. SURF w/o SEAS)

Vitz II (vs. Odyssey)

Figure 22. Passenger compartment deformation in car-to-car crashes.

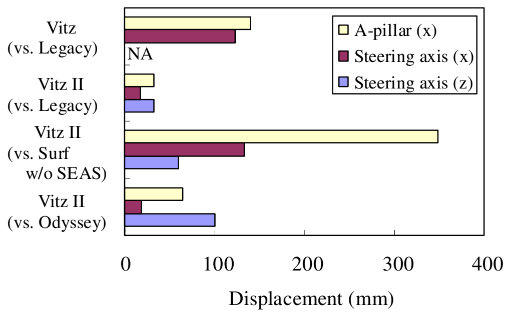


Figure 23. Passenger compartment intrusion of small car in car-to-car crashes.

DISCUSSION

In the present research, full-width rigid and deformable barrier crash tests were compared using a series of crash tests. A deformable element in full-width tests will be useful because shear deformation of the structures occurs and the local force of engine impact is mitigated. However, in full-width deformable barrier crash tests, for some cars with stiff bumper beam, the longitudinal members deformed in an unnatural mode in accord with rearward bending of the bumper beam. This deformation mode can affect sensor timing, especially with a seat belt pretensioner. Particularly for minicars and small cars, the deformable barrier effect is large because of the high acceleration of these cars, and the sensor delay can affect occupant interaction with airbag. It is still not clear how minicars or small cars optimized in full-width deformable barrier tests can affect the crashworthiness of these cars in real-world collisions.

Barrier forces of SUV with or without SEAS were examined. The results indicate that a reaction force from the SEAS can be evaluated using the peak row load in full-width deformable barrier crash tests. The target row load of 100 kN will be an acceptable threshold because the peak row load at the SEAS location decreased from 120 kN to 87 kN by removal of SEAS. Although it is also important for minicars and small cars to have longitudinal members with a ground-height in alignment with common interaction zone, further research will be needed to apply the SUV target row load 100 kN to minicars and small cars. This is because after ODB 64 km/h tests in NCAP, the compartment accelerations of minicars and small cars are already so high that high reaction forces required in common interaction zone can induce higher car acceleration, and acceleration-related injuries to occupants can increase even at low speed impacts.

The car-to-car crash test series using small cars indicated that the lateral and vertical mismatch of the longitudinal member can lead to the passenger compartment collapse of the small car. This situation will be improved after IHRA phase 1, when the structural interaction of SUV becomes acceptable. Although minimum strength of the passenger compartment is significant means to prevent the passenger compartment collapse, too strong a passenger compartment, on the other hand, can induce acceleration-related injuries. After structural interaction is improved, the stiffness matching and compartment strength will be important in controlling the intrusion and deceleration of the passenger compartment. The force matching and the compartment strength are important especially for the vehicle fleet where passenger cars occupy a large population like Japan.

CONCLUSIONS

A series of crash tests was carried out to assess vehicle compatibility. The results are summarized as follows:

1. Shear deformation occurs in full-width deformable barrier crash tests, and lateral members generate forces on the load cell barrier though the force level is small.
2. Full-width deformable barrier crash tests can be used as high acceleration tests. However, in full-width deformable barrier crash tests, the longitudinal member deformed inward, which can induce a crash sensor delay.
3. SEAS was detected in a full-width deformable barrier test, and VNT with a target row load of 100 kN will be a useful criterion to evaluate its force level.
4. Car-to-car crash tests showed that the guidelines of force matching and compartment strength will be needed to control and predict the passenger compartment intrusion.

ACKNOWLEGEMENTS

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STATUS OF ENHANCED FRONT-TO-FRONT VEHICLE COMPATIBILITY TECHNICAL WORKING GROUP RESEARCH AND COMMITMENTS

Saeed Barbat
Ford Motor Company
United States
Paper Number 05-463

ABSTRACT

This paper describes a part of ongoing progress and research conducted by the Front-to-Front Compatibility Technical Working Group (TWG) to enhance vehicle compatibility in vehicle-to-vehicle frontal crashes. As a short-term goal, the TWG developed and implemented Phase I performance criteria, based on static measurements of the Primary Energy Absorbing Structure (PEAS) height, to improve geometrical compatibility. This will enhance structural interaction, through better matching of frontal component geometries, between cars and light trucks, in frontal crashes. Options include better matching of bumper heights, longitudinal frame rail heights, and more evenly distributing impact forces across the fronts of vehicles. All participating manufacturers' new light trucks up to 10,000 pounds Gross Vehicle Weight Rating (GVWR), with limited exceptions, must meet Phase I requirements by September 1, 2009.

The focus of Phase II research for the TWG is the investigation and evaluation of Front-end performance. This will include research to investigate test procedures and performance metrics to assess potential dynamic front-end geometric, stiffness, and any other relevant performance characteristics that would enhance partner protection without any significant degradation in self-protection.

Test and simulation results obtained from frontal impacts with various Load Cell Walls (LCW) and from vehicle-to-vehicle impacts in various frontal impact configurations to support phase II research were analyzed and presented to help assess and improve vehicle compatibility. Average Height of Force (AHOF) obtained from frontal impact with LCW was investigated as a compatibility metric. Initial finding was the AHOF alone is insufficient metric and did not correlate with Aggressivity Metric (AM) defined by NHTSA. Alternative metrics and test procedures are under investigation by the TWG. Phase III research will focus on front stiffness matching between cars and trucks and also on passenger car compartment strength and integrity. The investigation will lead to the development of a test to determine appropriate front-end stiffness characteristics and criteria that would strike an appropriate balance between small vehicle passenger compartment strength and large vehicle energy absorption characteristics.

1. INTRODUCTION

The issue of crash compatibility of passenger vehicles has been around since at least the early 1970s when the widespread introduction of lightweight subcompact cars into a fleet of predominantly large and heavy cars caused some concerns. In recent years the trend of growing sales of sport utility vehicles and pickup trucks have led to renewed public attention to this issue. The National Highway Traffic Safety Administration (NHTSA) [1,2,3], The Insurance Institute of Highway Safety (IIHS), and The International Harmonization Research Activity (IHRA) have identified this trend and have increased the extent of their research in vehicle-to-vehicle compatibility.

The basic concern is the extent to which some vehicle design characteristics adversely influence the outcomes of two-vehicle crashes. Thus, in head-on crashes between two cars the risks for the occupants of the lighter cars increase as the weights of the heavier cars increase. Today, the crash compatibility focus has shifted from concerns about vehicle weight differences to the effects of differences in vehicle heights and front-end stiffnesses in crashes between cars and light trucks.

There are two approaches to improving crash compatibility among passenger vehicles. First and more important is to improve the protection a vehicle provides for its own occupants, which is sometimes referred to as "self protection." This approach is more important because it results in improved protection for vehicle occupants in all crashes, single-vehicle as well as crashes involving other passenger vehicles. Significant improvements in self protection have occurred over the past 20 years or so with the introduction of frontal airbags, better structural designs, increased belt use, etc., and as a result crash compatibility problems are smaller than they otherwise would have been. Self-protection enhancements can reduce occupant risks in all crash modes including frontal, side, and rear. The second approach to improving crash compatibility is to focus on vehicle design characteristics that can reduce the risks for occupants of other passenger vehicles, which is sometimes referred to as "partner protection." Partner protection improvements usually focus on changes to vehicle front-end designs for enhancing the structural interactions between the striking and struck vehicles.

2. BACKGROUND ON THE INDUSTRY AGREEMENT

Over the years individual auto manufacturers have made changes in their vehicles to enhance compatibility. However, in late 2002 the Alliance of Automobile Manufacturers decided to pursue a concerted industry-wide effort to develop performance criteria based on current "best practices," to further enhance vehicle compatibility. To start this process on February 11-12, 2003, the Alliance and the Insurance Institute for Highway Safety (IIHS) cosponsored an international meeting on enhancing vehicle-to-vehicle crash compatibility. Participants were not limited to these two groups; other international experts were included. NHTSA's Administrator Jeffrey W. Runge, M.D., opened the meeting by issuing a challenge to the industry for more progress on compatibility. Other speakers included representatives from Transport Canada, the United Kingdom's Transport Research Laboratory (TRL), the Alliance, Honda, and IIHS.

The technical presentations at the meeting laid the foundation for the industry to work on performance criteria to improve crash compatibility for the North American market. The data presented at the meeting highlighted potential opportunities to further enhance compatibility in both front-to-front crashes as well as front-to-side crashes. At the meeting, the participants agreed to set up two working groups of experts to develop initiatives and actions. One working group was established to address ways to improve compatibility in front-to-side crashes, the other to address front-to-front crashes. Each group included both industry and outside experts. Each group has developed initiatives and performance criteria that participating auto manufacturers are committed to adopt.

One of the key conclusions of the February 11-12, 2003, crash compatibility meeting was that a high priority should be assigned to addressing the issue of reducing injury risks in side impact crashes, especially when the striking vehicles are light trucks. In the short term, the meeting participants concluded that the most effective approach for this problem is to enhance self-protection for passenger vehicle occupants in side struck vehicles. Thus, the industry's specific commitment to enhanced front-to-side crash compatibility by improving self protection in side impacts covers light trucks (vans, pickups, and sport utilities) up to 8,500 pounds GVWR, as well as passenger cars.

In regard to front-to-front compatibility, the conclusions from the February 11-12, 2003, compatibility meeting was that improvements in frontal crash compatibility between cars and light trucks can best be achieved in the near term through improved partner protection. In particular, improved geometric matching between the front structural components of cars and light trucks is the most effective short-term approach, while better matching of frontal stiffness characteristics between cars and light trucks is a longer-term goal. It is important to not compromise the self-protection of occupants of light trucks as the front ends of these vehicles change to further improve partner protection.

Participating manufacturers started their research, investigation and proposed various phases for the development of compatibility performance criteria within two separate working groups for front-to-front and front-to-side compatibility. The working groups will transfer these performance criteria to appropriate internationally recognized voluntary standards to ensure the sustainability of these criteria. From this point in time, the focus of this paper will be on the results and criteria associated with enhancing front-to-front compatibility.

3. FRONT-TO-FRONT COMPATIBILITY WORKING GROUP COMMITMENTS

The TWG held its first meeting on March 10, 2003 and agreed on the following:

- A short-term initial step in addressing further improvements in front-to-front crash compatibility between two colliding vehicles is through better alignment and geometric matching of the vehicle crash structures.
- A barrier face load cell configuration with a 125mm x 125mm load cell array is appropriate to make the determination of the height and distribution of force of an impacting vehicle into the barrier face.
- The TWG agreed to review the use of a deformable face on the barrier for testing with NHTSA in order to ascertain the agency's willingness to include the deformable member as part of future (revised) FMVSS 208 barrier test procedures.

- The TWG agreed that achieving better alignment and engagement between the front-end structures of the impacting vehicles is the necessary first step towards improving compatibility. It was also agreed that manufacturers should begin designing light trucks so their PEAS (Rail or frame) overlap a proportion of the zone established by NHTSA in its bumper standard (49 CFR 581) for passenger cars. This zone of impact resistance for passenger car bumpers is the area between 16 and 20 inches off the ground. By ensuring that light trucks have a significant portion of their front energy-absorbing structures in this zone, these structures are more likely to engage (instead of over- or under-riding) the PEAS of passenger cars in a head-on crash.

4. PHASE I: ENHANCING GEOMETRIC ALIGNMENT OF FRONT ENERGY-ABSORBING STRUCTURES

The TWG developed the following Phase I requirements which were announced on December 3, 2003 as a first step towards improving geometrical compatibility: Participating manufacturers will begin designing light trucks in accordance with one of the following two geometric alignment alternatives, with the light truck at unloaded vehicle weight (as defined in 49 CFR 571.3):

OPTION 1: The light truck's primary frontal energy-absorbing structure shall overlap at least 50 percent of the Part 581 zone AND at least 50 percent of the light truck's primary frontal energy-absorbing structure shall overlap the Part 581 zone (if the primary frontal energy-absorbing structure of the light truck is greater than 8 inches tall, engagement with the entire Part 581 zone is required), OR, **OPTION 2:** If a light truck does not meet the criteria of Option 1, there must be a secondary energy-absorbing structure, connected to the primary structure, whose lower edge shall be no higher than the bottom of the Part 581 bumper zone. This secondary structure shall withstand a load of at least 100 KNewtons exerted by a loading device, as described in the attached Appendix A, before this loading device travels 400 mm as measured from a vertical plane at the forward-most point of the significant structure of the vehicle.

If a light truck has crash compatibility devices that deploy in high-severity frontal crashes with another vehicle, all measurements shall be made with these devises in their deployed state. Not later than September 1, 2009, 100 percent of each participating manufacturer's new light truck production intended for sale in the United States and Canada will be designed in accordance with either geometric alignment Option 1 or Option 2.

Applicability All light truck vehicles with a GVWR up to 10,000 pounds, except, low production volume vehicles, vehicles over 8,500 pounds GVWR with functional criteria which preclude them from meeting the performance criteria, (e.g., postal vehicles, military vehicles, service vehicles used by public and private utilities, vehicles specifically designed primarily for off-road use, and incomplete vehicles), and other vehicles that a manufacturer determines cannot meet the performance criteria without severely compromising their practicality or functionality.

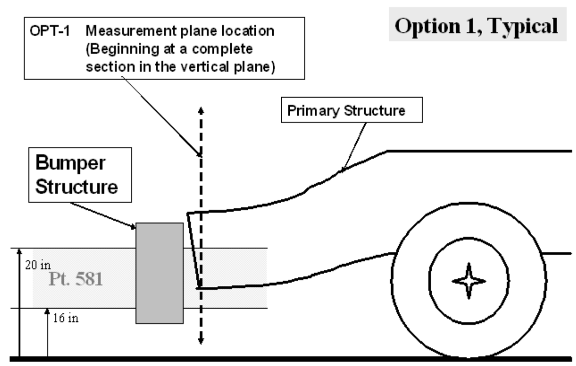


Figure 1. Typical front rail geometry and definition of Part 581 zone for voluntary standard.

Product Information Beginning November 3, 2003, and on each September 1st thereafter, through September 1, 2009 (i.e., November 3, 2003; September 1, 2004; September 1, 2005; September 5, 2006; September 3, 2007; September 1, 2008; and September 1, 2009), participating manufacturers will publicly disclose at least annually, the vehicle nameplates [models] for the upcoming model year that have been engineered according to the front-to-front and front-to-side performance criteria, and provide a 'good faith' estimate of the percentages of the manufacturer's total production for the upcoming model year that are engineered in accordance with the front-to-front performance criteria, respectively.

Confirmatory Data: Beginning November 3, 2003, and on each September 1st thereafter, through September 1, 2009 (i.e., November 3, 2003; September 1, 2004; September 1, 2005; September 5, 2006; September 3, 2007; September 1, 2008; and September 1, 2009), participating manufacturers shall voluntarily provide to NHTSA confirmatory data, engineering judgment, or other analyses demonstrating that vehicles identified above have been designed in accordance with the front-to-front and front-to-side performance criteria, respectively.

5. PHASE II RESEARCH

The TWG developed a matrix of physical tests and simulations in relation to rigid wall barrier impact, full width deformable barrier impact, and vehicle-to-vehicle impact to generate data to support Phase II research (see matrix shown in Appendix B). The purpose of this research phase was three fold. Firstly to identify a dynamic test procedure that evaluates geometrical changes made in vehicles. Secondly, existing metric proposals such as AHOF should be evaluated. Lastly, to evaluate test methods to measure front-end stiffness and develop potential actions to further enhance compatibility between vehicles.

The initial focus of the TWG was on the AHOF to be used as a metric for compatibility to enhance structural interaction between vehicles during frontal impact. The test methods evaluated were full-frontal impacts against a barrier fitted with load cells, load cells covered with a honeycomb (TRL Barrier Face) or without a honeycomb (similar to MIRA Barrier). Other TRL-type LCW with deformable elements such as the one shown in Figure 2 was also used. However, this barrier is 50mm from the ground and has 125mm x 125mm load cell in the interaction zone only, compared to that of TRL barrier which has 125mm x 125 mm load cell array, sixteen cells wide and ten cells high.

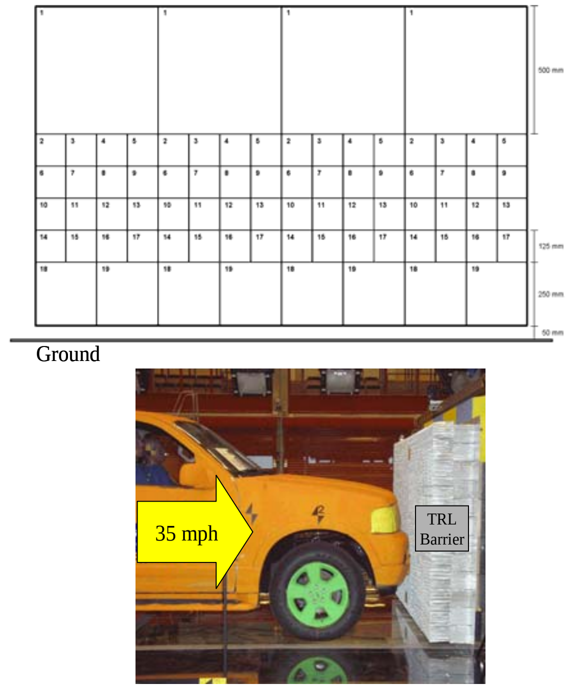


Figure 2. TRL-Type 125x125mm load cell deformable barrier.

Most of the tests and/or simulation planned on Appendix B were executed and completed by the Alliance participants. Although several geometric parameters or metrics such as Height of Force (HOF), AHOF, Homogeneity factors (CV), load distribution, row's force limit, cell force limit, row force percentage, deformation based, and other metrics in the interaction zone can be obtained and investigated, the initial focus of the research was on the AHOF calculation obtained from 56 kph frontal impact with TRL/TRL-type deformable barrier or rigid barrier tests. In addition, vehicle-to-vehicle frontal impact tests and real-world accident data analyses were conducted to validate the relation between the AHOF metric, as a compatibility metric, and the outcome of the occupant injury from crash tests and traffic accidents. Figure 3 shows an example of the load-time history of each cell obtained from a 56 kph impact of a mid-sized SUV. On the same figure it also shows the part 581 zone and locations of the PEAS of typical SUV and passenger cars. Figures 4-6 show typical results such as the HOF, load distribution or load percentage at each row and the deformation or the footprint on the deformable face as potential metrics.

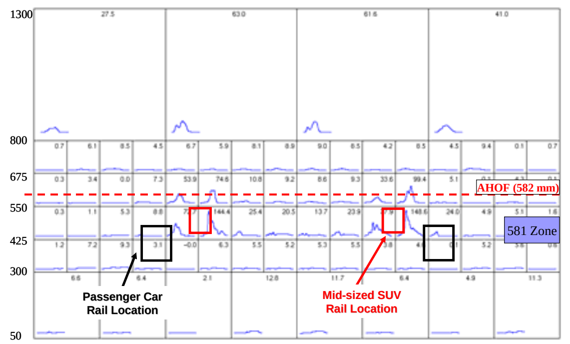


Figure 3. Example of Force-Time history distribution for TRL-type barrier with 125 x 125mm load cells.

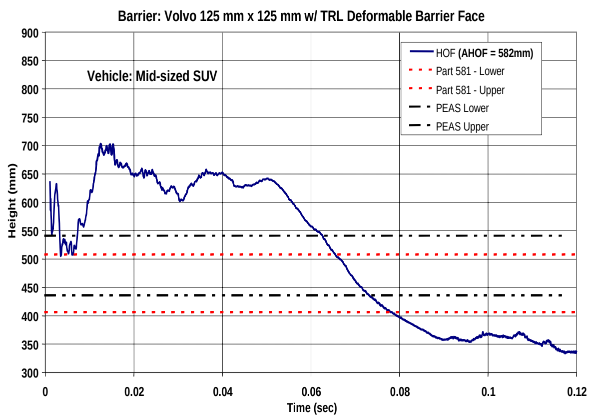


Figure 4. Example of HOF-time history for TRL-type barrier with 125 x 125mm load cells.

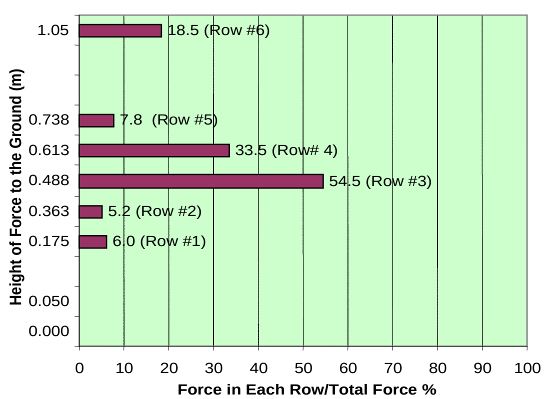
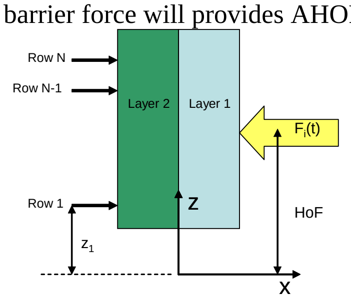


Figure 5. Example of normalized row force distribution for TRL-type barrier with 125 x 125mm load cells.

Figure 6. Example of foot print obtained on a TRL-type barrier deformable face.

5.1 HOF and AHOF Analyses and Conclusions

Figure 7 shows schematic and mathematical definitions for calculating the HOF and AHOF when a force is applied to a barrier, either deformable or rigid, in a normal frontal impact. If all load cells along a certain height are grouped together, the so-called row force may be determined and the height of force (HOF) can then be computed. Normalizing this time dependent height measurement by the total barrier force will provides AHOF.



$$HoF(t) \equiv \frac{\sum_{i=1}^{N} RF_i(t) \cdot z_i}{\sum_{i=1}^{N} RF_i(t)}$$

$$\text{AHoF} \equiv \frac{\sum_t HoF(t) \cdot F_i(t)}{\sum_t F_i(t)}$$

where N is the number of rows and RF_i is the force in row i

Figure 7. Diagram and definition of HOF and AHOF.

TWG members have reported results from crash tests and/or CAE simulations obtained from 56 kph impacts with 125mm x 125 mm rigid LCW, 50mm x 50mm rigid LCW, 125mm x 125 mm deformable LCW using HOF or AHOF metrics. In addition, some of the member companies have conducted vehicle-to-vehicle crashes (test and/or simulation) as a validation. An analysis of NHTSA's data on Aggressivity Metric (AM) was also conducted to obtain its correlation with AHOF.

When AHOF is calculated for several vehicles it may be compared to the geometrical location of their primary energy absorbing structures. This is done for a small sample of vehicles as shown in Figure 8. Vehicle-to-vehicle crash tests of mid-sized SUV1 (4x4) without SEAS and full-sized SUV (4x2) with blocker beam against a mid-sized passenger car in full frontal impact were also conducted. The AHOF for both SUVs are shown in Figure 8, where HD PU (heavy duty pick-up) AHOF corresponds to that of the full-sized SUV. Both the target and bullet vehicles used a Hybrid III 50th percentile male dummy for the driver and a Hybrid III 5th percentile female dummy for the passenger. The driver seat was at the mid-position while the passenger seat was full-forward. The target vehicle was stationary and the bullet vehicles were moving at a speed adjusted according to impacted vehicles mass ratio to impart a 56 kph velocity change in the target vehicle, which is the passenger car in this case. Figures 9 and 10 show the geometrical alignment, superimposed on 581 zone, for both SUVs front-end structures against that of the passenger car.

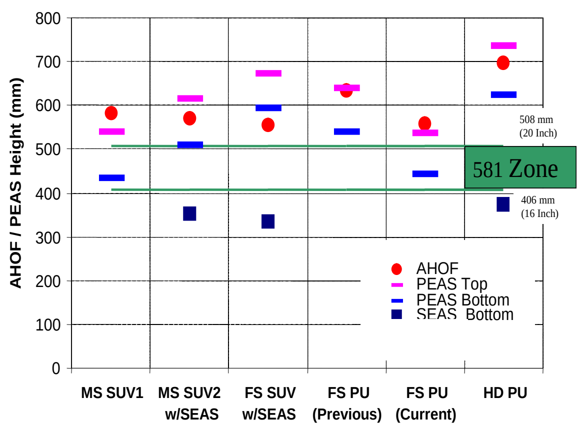


Figure 8. Comparison of AHOF for several vehicles.

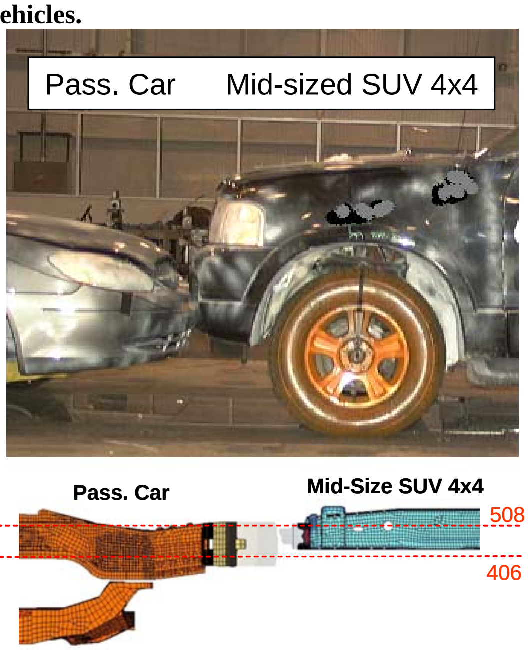


Figure 9. Mid-sized SUV1-to-Passenger car impact.

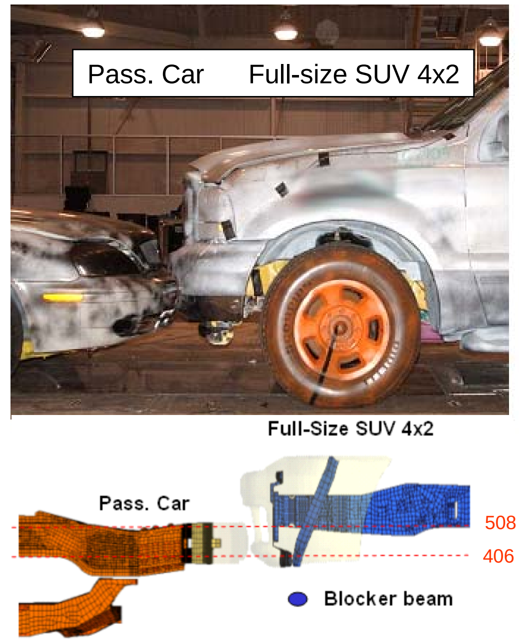


Figure 10. Full-sized SUV-to-Passenger car impact.

Figures 11 shows the driver injury responses of the target vehicle resulted from impacts with mid-sized SUV1 and full-sized SUV that differs in AHOF magnitudes. The injury numbers were normalized to the NCAP values. Occupant responses of the driver hit by full-sized SUV with blocker beam are less severe compared to those resulted from impact with mid-sized SUV1. Comparing results from Figures 8 and 11 it is very clear that the AHOF does not show the beneficial effect of the blocker beam on compatibility demonstrated in vehicle-to-vehicle crash tests. The Full-sized SUV with blocker beam has the highest AHOF compared to that of the mid-sized SUV1 as shown in Figure 8.

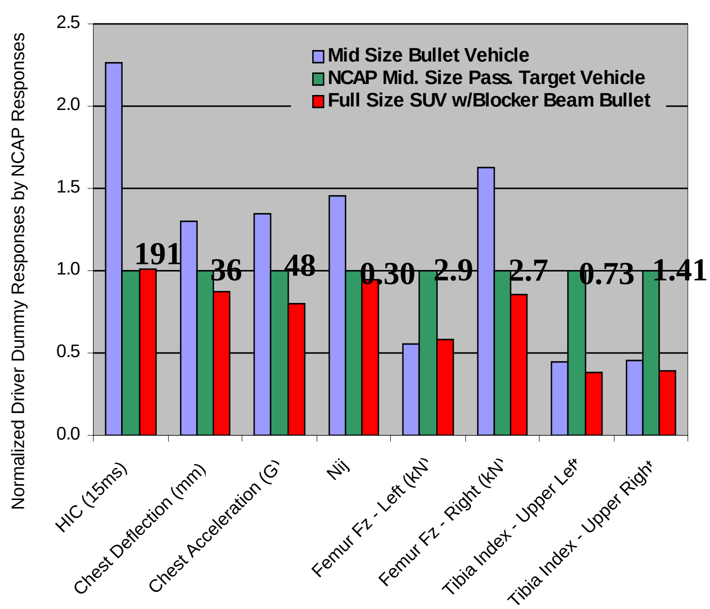


Figure 11. 50th % HIII driver dummy responses of target vehicle.

A separate study considered lowering the overall vehicle height 38 mm and studying the corresponding effect on AHOF [4]. This study concluded that there was little difference in overall AHOF values when vehicle with significantly different PEAS heights were tested against a load cell barrier. In other words, as seen from the data presented in Figures 12 and 13, the HOF and AHOF have significant errors in indicating the change in the actual height of a vehicle and of its structure.

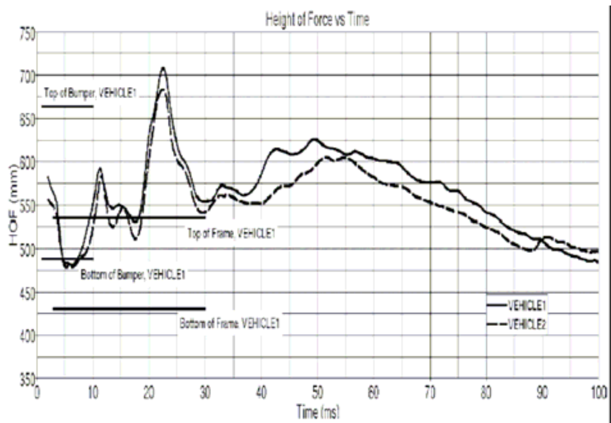


Figure 12. HOF(t) for base vehicle and when lowered 38 mm.

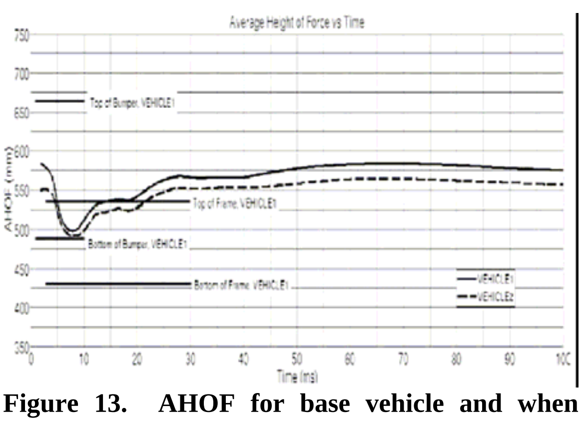


Figure 13. AHOF for base vehicle and when lowered 38 mm.

Conclusions from testing against load cell walls, deformable face barriers, and vehicle-to-vehicle test are that AHOF is not a sufficiently sensitive metric to evaluate the height of the front rail and the effect of SEAS on compatibility. The AHOF does not show the beneficial effect of the Blocker Beam on compatibility demonstrated in the vehicle-to-vehicle tests.

In an effort to determine the correlation between the AHOF measurement and field experience, the fatality related Aggresivity Metric (AM) and AHOF were compared for several vehicles in various categories [5] [1]. To evaluate the characteristics of the vehicle compatibility problem, NHTSA [6] has developed the Aggressivity Metric (AM) which uses the number of driver fatalities in a collision partner normalized by the number of collisions of the subject vehicle (only two vehicle collisions are used) [2]. AM is defined through the relationship:

$$\text{Aggressivity Metric} = \frac{\text{Driver Fatalities in collision partner}}{\text{Number of Crashes of subject vehicle}}$$

The data for this analysis was gathered from two sources. First, AHOF data was obtained from the results of NCAP vehicle tests, measured by a load cell wall, provided by NHTSA. The AM data was provided by NHTSA. The number of vehicle models corresponding to the data appears in Table 1.

1 Toyota Previa Van and T100 PK are included in this analysis even without MY information for the AM value because there was no model change. Therefore, the available AHOF value from any MY of these vehicles can correspond to its AM value.

2 CGNO7424 Ford F150 Pickup Frontal AM (126)

CGNO7628 Chevrolet Tahoe Frontal AM (167)

Table 1.

Number of Vehicle Models Represented in the Datasets

	AM		AHOF
	Front Collision	Side Collision	
# of Vehicles Models	183	201	636

Assumptions

AHOF data was available for a specific subject vehicle from a single model year (MY). However, the AM data did not necessarily correspond to a single MY and therefore, the data was divided into four categories depending on the nature and availability of the dataset:

$MY_{xx} \sim MY_{yy}$

An AM value for a subject vehicle in the range $MY_{xx} \sim MY_{yy}$ is paired to an AHOF value for a given MY of the subject vehicle in that range. If there are multiple AHOF values that apply to the $MY_{xx} \sim MY_{yy}$ range, then an average is calculated. If the subject vehicle model has many model changes[1] in the MY for which 1 AM value is available and if AHOF values are not available for all model changes within that MY, then the subject vehicle is not included in this analysis.

$MY_{xx} \sim$

In this case, the life of the model is unclear; therefore, the life is assumed to be 4 years. An AHOF value for a particular MY is identified with the AM value for vehicles from MY_{xx} to MY_{xx+4}. If there are multiple AHOF values for vehicles that fit into the range MY_{xx} to MY_{xx+4}, then an average AHOF is calculated.

$\sim MY_{yy}$

In this case, the beginning of the life of the model is unknown. Using the same assumption for model life from #2 above, an AHOF value for a particular MY is identified with the AM value for vehicles from MY_{yy-4} to MY_{yy}. If there are multiple AHOF values for vehicles that fit into the range MY_{yy-4} to MY_{yy}, then an average AHOF is calculated.

MY not listed: For AM values that do not have a MY available, it is not possible to identify a corresponding AHOF value and that particular vehicle cannot be included in the analysis[1]

If there are multiple vehicle models with the same AM value, then an average AHOF value is calculated. The drive train (2WD, 4WD, etc.) is listed in neither the AM nor AHOF datasets. The information on vehicles from the AM dataset includes a designation for the number of doors on a subject vehicle (2-door or 4-door). If the number of doors is not specified for the AHOF value of a subject vehicle, then the vehicle is assumed to be a 4-door vehicle and identified with the AM value for the 4-door subject vehicle. Finally, two outliers with comparable high AM values were excluded.[2]

After applying the above assumptions, the dataset is described in Table 2. Since several AHOF values may be identified with one AM value, AHOF values are used for this analysis to enhance the n-value of the dataset. Further, the number of models with available AHOF data is greater than the number of models with AM data. The database was divided into two categories. Front-to-front corresponds to vehicles colliding in the x-direction from 11 to 1 o'clock. The front-to-side condition corresponds to vehicles struck on either side (7 to 11 o'clock or 1 to 5 o'clock) by the front of the bullet vehicle.

Table 2.

Vehicle Models with Corresponding AM and AHOF Data

	AM Data	AHOF Data
Vehicle models used for front-to-front analysis	77 models (42%)	143 models
Vehicle models used for front-to-side analysis	80 models (40%)	149 models

The data was grouped by vehicle type and by mass. In Figure 14, results by vehicle type show that for passenger cars the correlation was extremely low ($R^2 = 0.002$). For SUVs, AM tends to decrease with increasing AHOF, however this correlation is also extremely low ($R^2 = 0.3$). Conversely for Vans, AM tends to increase with increasing AHOF, also with low correlation ($R^2 = 0.05$). Such low correlation values, whether for increasing or decreasing relationship between AM and AHOF, suggests no relationship between the two variables.

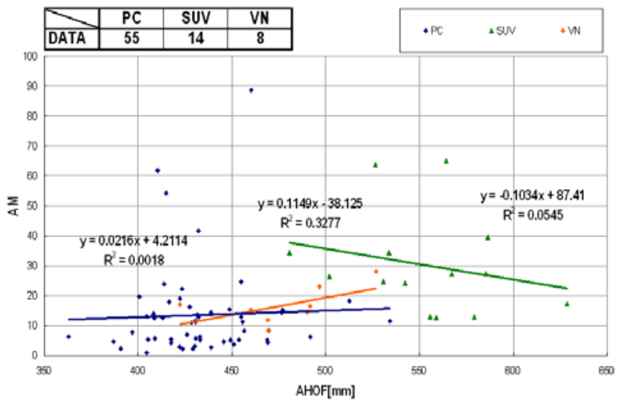


Figure 14. Correlation between the Aggresivity Metric and AHOF for vehicle types.

Finally, the vehicles were divided into weight classes based on their GVWR and the results are presented in Figure 15. The weight classes range from 1000kg to 3000kg in increments of 500 kg giving a total of 4 weight classes. This classification was performed to eliminate any confounding effects due to the different weights. Again it was seen that there was no significant difference in the relationship between AM and AHOF for different weight classes.

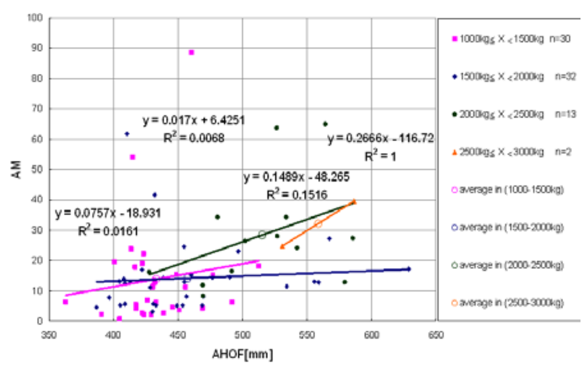


Figure 15. Correlation between the Aggresivity Metric and AHOF for vehicle weight class.

From this study, it can be concluded that there is poor correlation between AM and AHOF. In terms of fatalities, evaluating vehicles using AHOF alone will not necessarily provide reductions in vehicle aggressivity in the field. Continued research of appropriate metrics is recommended to evaluate measures that will improve field compatibility. With AHOF discounted as single compatibility metric, several subgroups were formed to further study vehicle compatibility tests and metrics. At Phase 2, the TWG concluded that geometric compatibility is an important first step to improve compatibility between vehicles. Also, stiffness and geometry must be considered together for the long-term direction of further improvements in fleet-wide compatibility. The current AHOF/HOF definition alone is no sufficiently sensitive to discriminate changes or variations in front-end structures that are beneficial for compatibility. Based on this the TWG formed three sub-groups to support phase II research

6. PHASE II, SUBGROUP 1: FIXED BARRIER TESTS AND METRICS

This subgroup was organized to evaluate potential changes to the TRL deformable barrier to improve SEAS detection and to explore new LCW metrics that could be used with a full overlap test to predict structural interaction. It was determined that a deformable element barrier should be used for investigation in lieu of a rigid wall for several reasons. Foremost is that a deformable barrier would allow for improved detection of secondary energy absorbing structure, which can be set back from the front of the vehicle and otherwise undetectable in an impact with a rigid wall. A deformable barrier can also reduce the high decelerations that can result from stress wave effects at the front of the rails in rigid wall impacts with the effect that the initial phase of the impact is more representative of vehicle-to-vehicle impacts. Additionally, deformable barriers reduce engine dump loading that may otherwise confound the measured force data and can detect strain effects due to cross-car load transfer through crossbeam structures.

Where appropriate, barrier tests designed to assess compatibility should be adaptable to current NCAP / FMVSS 208 test setups, in order to minimize number of tests necessary during vehicle development. The baseline deformable barrier was developed by TRL consisting of two 150 mm thick layers of aluminum honeycomb. The stiffness of the layers is 0.34 MPa and 1.71 MPa for the front and rear layers, respectively. The second layer of the baseline barrier is segmented along each load cell row and column, meaning the deformable layer will not transfer load to adjacent cells. Using this design as a baseline configuration, three modifications were identified for exploration (seen in Table 3).

Table 3.
Barrier configurations considered for evaluation

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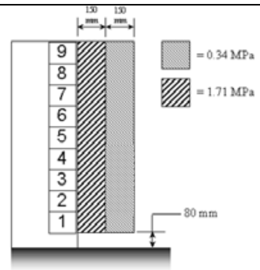
<tr><td>Baseline (TRL) Barrier</td><td>
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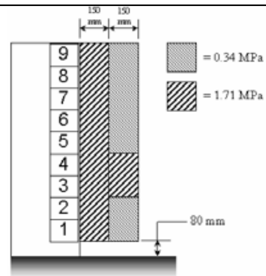
<tr><td>Barrier 1</td><td>
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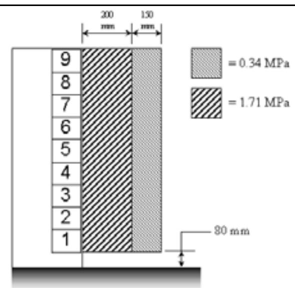
<tr><td>Barrier 2</td><td>
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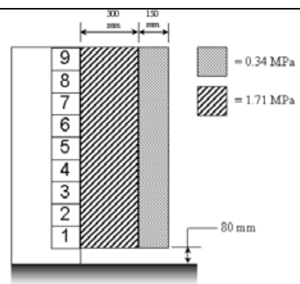
<tr><td>Barrier 3</td><td>
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Barrier 1 adjusts the stiffness of only rows 3 and 4 in the front-most layer to 1.71 MPa. The intended purpose here was to provide a path for the secondary energy absorbing structure (SEAS) to transfer force to the barrier. The second barrier and third barriers increase the thickness of the second layer by various degrees to determine if added depth would allow the barrier to reach further back into the test vehicle to pick up the SEAS. In the case of the third barrier, the rear layer is not segmented as it is in the baseline TRL barrier. This is necessary to avoid crush instability in the honeycomb. Four metrics were proposed by the TWG for barrier evaluation, as defined in Tables 4 and 5.

Table 4

Definitions for proposed barrier metrics

Metric 1: Total force in select rows	$\mathrm{M1} \equiv \max_t\left[RF_3(t) + RF_4(t)\right]$
Metric 2: Total force % in select rows	$\mathrm{M2} \equiv \dfrac{\max_t\left[RF_3(t)\right] + \max_t\left[RF_4(t)\right]}{\sum_{i=1}^{N} \max_t\left[RF_i(t)\right]}$
Metric 3: Homogeneity, distribution of force in selection area	$\mathrm{M3} \equiv \dfrac{\sum_{i=1}^{nc}\left(\dfrac{L - f_i}{L}\right)^2}{nc}$
Metric 4: Distribution of deformation into layer 2 in Evaluation Area	$\mathrm{M4} \equiv \dfrac{A_C}{EA}$ for all $u_x^{Frt}(y,z) > 150\mathrm{mm}$
Other Metrics have also been proposed such as vertical and horizontal [negative] deviation from a target value.	

Table 5.
Notation used in metric definitions.

$$A_C \equiv \begin{cases} \text{Area of the simple, closed curve defined} \\ \text{by nodes/points with} > 150\,\text{mm deformation.} \\ \text{Green's Theorem} \Rightarrow A_C = \frac{1}{2}\int (y\,dz - z\,dy) \end{cases}$$

$$f_i \equiv \text{(peak) load } F_i(t) \text{ in load cell } i \text{ in HSA} = \max_t\left[F_i(t)\right]$$

$$EA \equiv \text{Evaluation Area, } 250 \cdot 1500 = 375{,}000\,\text{mm}^2$$

$$HSA \equiv \text{Homogeneity Selection Area}$$

$$L \equiv \text{(peak) average load per cell in } HSA = \frac{\sum_{i=1}^{nc} f_i}{nc}$$

$$nc \equiv \text{number of load cells in } HSA$$

$$N \equiv \text{number of barrier Rows}$$

$$RF_i(t) \equiv \text{Force-time history of Row } i$$

$$TF(t) \equiv \sum_{i=1}^{N} RF_i(t)\text{, force-time history for barrier}$$

$$u_x^{Frt}(y,z) \equiv \text{axial displacement for nodes on front barrier face lying within EA}$$

Homogeneity Selection Area is the area covered by load cells lying in rows whose peak row force is > 5% of the peak total force AND whose peak column force is > 3% of the peak total force.

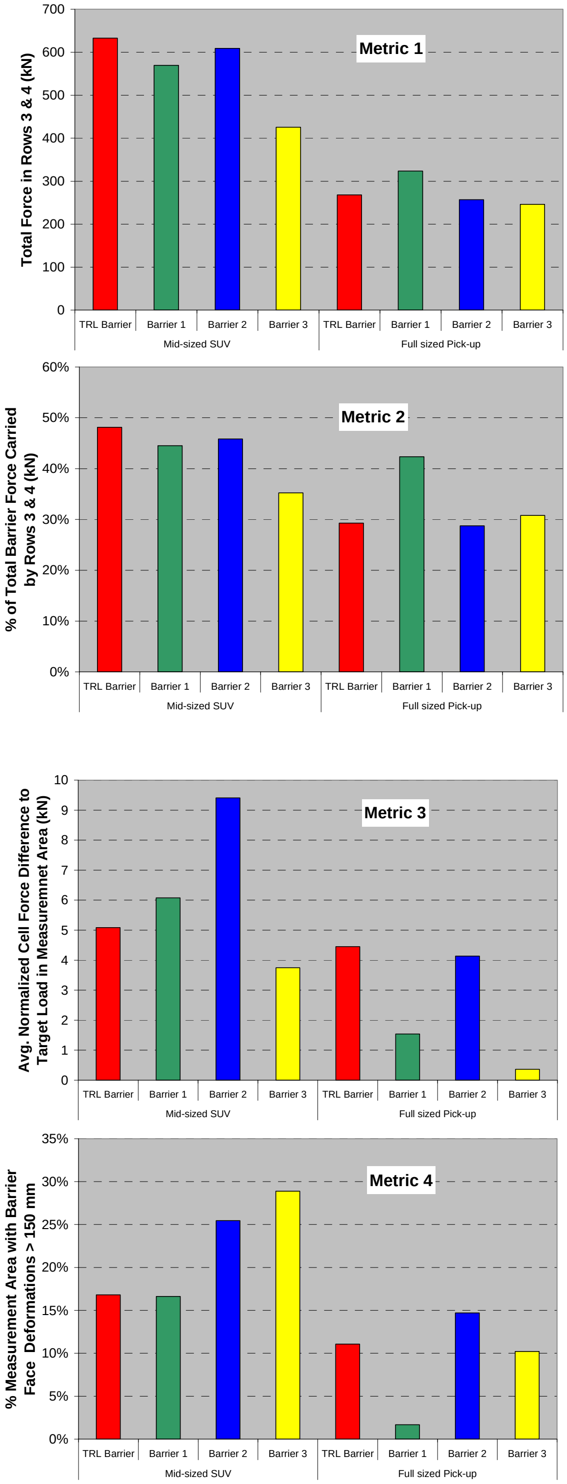
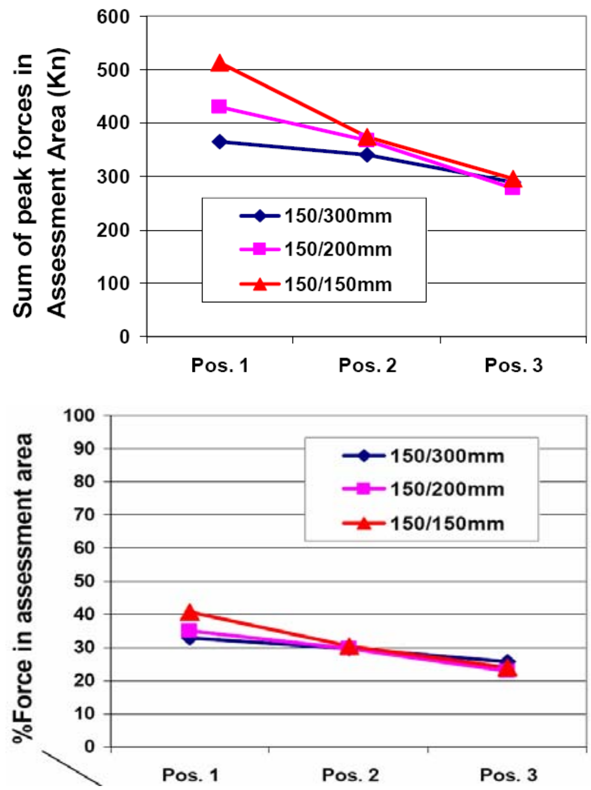


Figure 16. Comparison of for metrics for various barrier designs using simulation.

Barrier 1 adjusts the stiffness of only rows 3 and 4 in the front-most layer to 1.71 MPa. The intended purpose here was to allow the secondary energy absorbing structure (SEAS) to transfer force to the barrier. The second barrier increases the thickness of the layer 2 to 200 mm. The third barrier configuration continues to thicken the second layer to 300 mm as well as eliminating the segmentation of it. This non-segmented characteristic was intended to investigate the possibility of capturing the lateral load transfer actual vehicles experience

Metrics one and two use a force-based criterion to measure barrier differences. A third study investigated changing the location of a SEAS structure on detection by layered barriers. A change in the depth of the second layer did not appear to affect the detection of SEAS as seen in Figure 17 below.



$$\frac{\sum \text{force maxima within assessment area}}{\sum \text{force maxima total}}$$

Figure 17: Effect of changing the forward position of SEAS on force in an assessment area.

It can be seen from Figure 17 that changing the depth of the second barrier layer leads to less effective SEAS detection. Examining current test results with rigid barriers (LCW), deformable barriers (LCW), and further work has been initiated to develop a simple test procedure and metrics using a LCW as a compatibility measurement tool.

The subgroup has also investigated the International Harmonized Research Activity (IHRA) compatibility working group phase I test proposal [7]. The test configuration is a full width test carried out at 56 km/h into a wall equipped with an array of 125 mm x 125 mm load cells and the TRL deformable barrier face. The aim of the proposal is to ensure that all vehicles have sufficiently strong structure in a common interaction zone. This zone is defined vertically as 330-580 mm high, essentially the third and fourth load cell rows when the LCW is positioned with a ground clearance of 80 mm. A new metric based on peak cell loads has been proposed. It consists of vertical and horizontal components. These are complementary but could be applied separately.

The aim of the vertical component is to ensure that there is sufficient vehicle structure in alignment with the common interaction area. It sets a target row load and calculates the load below the target row for each row in the common interaction zone, i.e. rows 3 and 4.

$$D_{VNT} = \sum_{Row(i)=3}^{4} IF\left[\{R_i \leq TR_i\} THEN, ABS(R_i - TR_i),\ ELSE = 0\right]$$

where:

Row Load $R_i = \sum_{j=1}^{allcolumns} f_{ij}$

TR_i = Target row load
F_{ij} = peak cell load

If a performance limit of zero is required for this metric, then it is effectively a minimum row load requirement. The subgroup examined test data from 8 FWDB tests with various LTVs and showed that a row load greater than 100 kN was a good indicator if the LTV had either PEAS and / or SEAS in alignment with that row provided that the SEAS had a crossbeam structure.

The aim of horizontal component is to assess if crossbeam(s) or comparable structure on SEAS have sufficient strength. The metric would encourage a crossbeam strength that tended to match the stiffness of the front of the longitudinals. It sets a target cell load for the row based on the total row load and calculates the load below target cell load for each cell between the rails for each row in the common interaction zone. The subgroup intends to evaluate this metric further in future work.

In summary, the subgroup intends to perform additional work to evaluate the IHRA proposal.

Major issues that this work will address include the test robustness, in particular its sensitivity to the vertical alignment of the vehicle with the LCW, and validation, including the degree to which the metric affects the fleet and the benefits of changing to meet it. The TWG will continue their research to evaluate the proposed and new compatibility metrics.

7. PHASE II, SUBGROUP 2: VEHICLE-TO-VEHICLE OR MDB-TO-VEHICLE IMPACT TEST

The purpose of this subgroup's activities was to study vehicle-to-vehicle impacts with the focus of developing a performance protocol for classification of the under-ride/over-ride condition and also to provide an alternative performance procedure to simplify the geometry matching of PEAS/SEAS. Additional research will be towards development of a uniform test protocol for Phase-III research.

Figure 18. Full-frontal, vehicle-to-vehicle testing between mid-sized SUV and passenger car.

Figure 19. Full-frontal, MDB-to-vehicle testing for passenger car.

Objectives for this task are the development of requirements for vehicle-to-vehicle simulation and crash tests to demonstrate the minimization of Under-Ride/Over-Ride in a vehicle-to-vehicle frontal impact conditions. It is desired to establish a single standard partner (the struck) vehicle to be used for all tests. This vehicle will be a mid-size passenger car and will be representative of a model with a four-star rating and a weight around 1600 kg. The moving deformable barrier (MDB) will represent this average. And each OEM will be able to test a mid-sized vehicle (~1750 Kg, 4*, Acceptable) with it. The MDB would provide an equivalent target for all OEM compatibility testing.

The goal of establishing a uniform test vehicle is to enable manufacturers to start engineering for improved compatibility as soon as possible. Therefore, it is recommended that a manufacturer be allowed to select a vehicle as a 'reference passenger car' according to the following three criteria: First, select a high volume mid-size or smaller passenger car that is sold in the USA as a regular production vehicle and the vehicle mass should not exceed 4000lbs (NHTSA NCAP test configuration). Secondly, the vehicle must be rated at least as 4 stars in US Frontal NCAP test. Lastly, the vehicle must be rated as at least 'Acceptable' in IIHS ODB tests. These target characteristics will ensure a good balance between equitable requirement and a quick start. The TWG will undertake the development of one uniform test vehicle surrogate as mentioned earlier. The first priority test mode will be Full overlap using 50th & 5th percentile dummies, and the second priority will be partial overlap, again using 50th & 5th percentile dummies. Determination of the particular measurement criterion is an ongoing issue. Potential candidates are the use of NASS data including partner vehicle acceleration and cabin intrusion, occupant performance measures, and IIHS intrusion values.

The first option for the measurement of injury is occupant compartment accelerations using both vehicles front and rear sills, similar to the NCAP test. The use of the dummy's injury values (as in full-frontal and offset testing) are options. In this case, the performance criterion for this test would be pulse severity not to exceed the US-NCAP performance. Secondly, occupant compartment intrusion values are being considered. Here, a partial overlap test could be utilized and the body side aperture deformation measured. Open issues are the selection of a target vehicle and the selection of static post-test points to be measured (e.g. I/P, Dash, Cowl, Toe-Board, or the steering column).

It should be noted that an additional over-ride/under-ride performance criterion is being considered. If in the NCAP full frontal test, a plane of maximum crush is established, the "NCAP plane", is defined, then a "Safety Zone" extending from the NCAP plane to a reference point (for instance the 'A' Pillar, Windshield, etc.) would be defined (see Figure 20). Future structural designs under consideration should ensure that the rails of the LTV do not intrude into the safety zone beyond a [TBD] value.

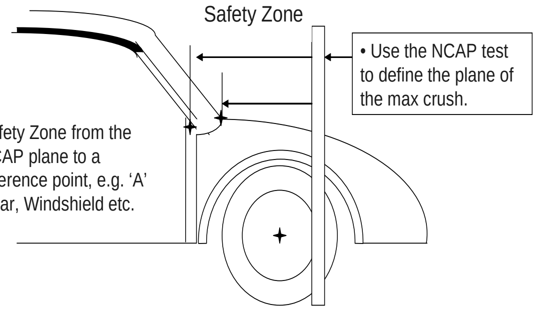


Figure 20. Definition of "NCAP safety plane".

8. PHASE II, SUBGROUP 3: SUPPLEMENTARY TEST FOR SEAS EVALUATION

Efforts for this subgroup's activities centered on development of a performance metric and evaluation procedure for Secondary Energy Absorbing Structure (SEAS) that meet the criteria proposed in TWG Phase I recommendations (Option 2). SEAS Evaluation Candidates investigated were the Dynamic Override Barrier test and Quasi-static test based on ECE R93 (Front Under-run Protection). Both tests and simulations were conducted for development of this evaluation.

The Subgroup examined SEAS structures with respect to over-ride potential through the test setup seen in Figure 21. For a test vehicle weight of 1967 kg with a speed of 19.8 kph and barrier upper surface height of 508mm, the strength (force-displacement performance) of the primary front structure components was determined. The overlap of the barrier with the bumper beam is 56mm, however, the frame (PEAS) did not overlap the barrier since the barrier width was 400mm.

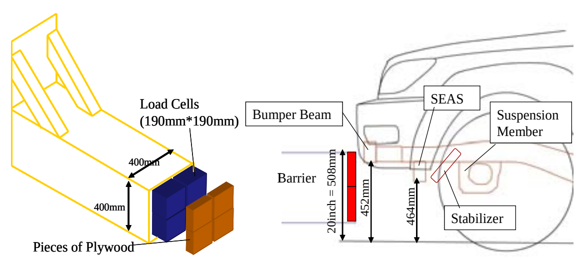
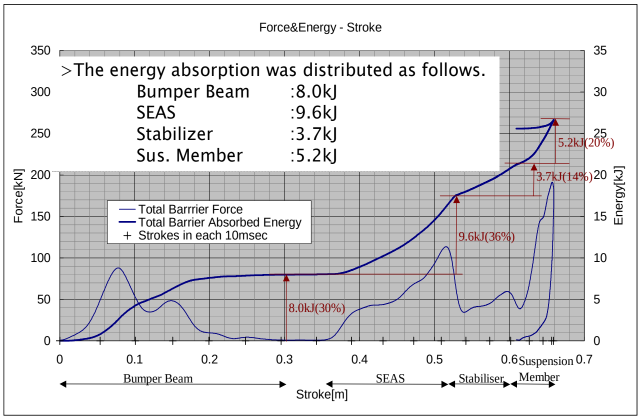


Figure 21. A proposed hardware and test setup for over-ride and SEAS strength testing.



Force-Stroke and Energy-Stroke of total barrier force

Figure 22. Force-displacement performance for various front structure components.

This test showed an energy distribution between the bumper beam, SEAS, stabilizer bar, and suspension members of 8.0, 9.6, 3.7, and 5.2 kJ, respectively. It should be noted from Figure 22 that there is 150 mm stroke span between the bumper beam and initial force accumulation of the SEAS. The majority of the energy is dissipated by the bumper beam and SEAS.

SUV-to-Barrier Simulation included SUV-to-override barrier (full width barrier = 2000 mm). The barrier was lowered to clear other front structures and impact the SEAS first and the vehicle speed was 56 kph.

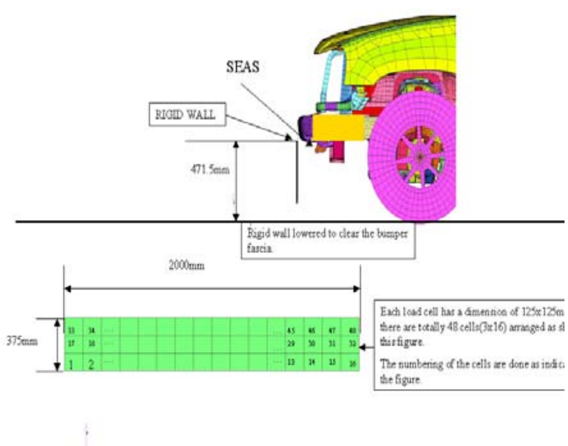


Figure 23. Partial rigid wall simulation for evaluation of SEAS.

The SEAS evaluated were shown to be effective though direct loading simulations by a partial rigid wall (see Figures 23 and 24).

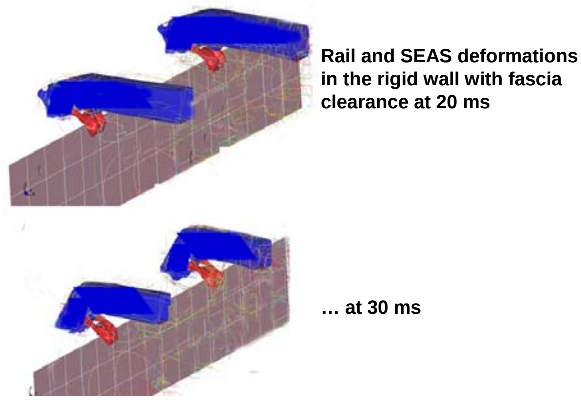


Figure 24. Rail deformations when impacted by a partial rigid wall.

This additional proposal was a low, continuous load cell barrier. Simulations were done where only the SEAS were contacted to evaluate their effectiveness. The effectiveness of SEAS was first examined in vehicle-to-vehicle tests and in these simulations.

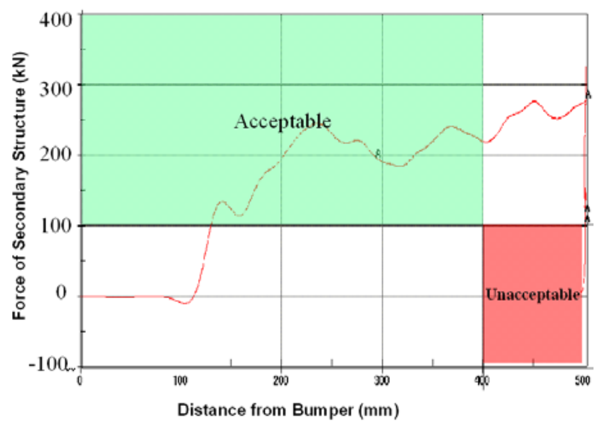


Figure 25. Proposed force – displacement ranges of acceptability for SEAS.

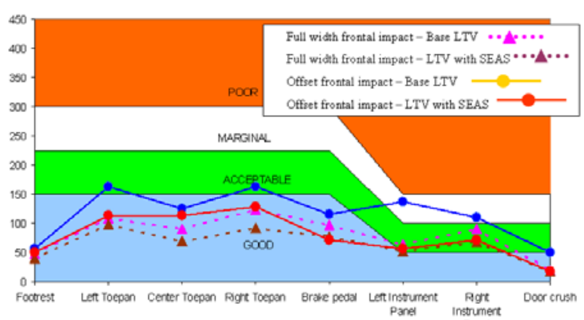


Figure 26. Ranges of acceptable performance for LTV with and without SEAS.

SUV-to-car simulations including non-continuous and continuous SEAS were investigated by the subgroup 3. For all SUVs simulated (2100kg – 2900kg), the SEAS was shown to be effective in reducing intrusions to the struck car (Figure 26) if a minimum force of 60 kN is seen by each rail with less than 400 mm of displacement. This amounts to a total force of 120 kN on the SEAS.

The TWG has agreed on the following test procedures and performance criterion for SEAS. The SEAS shall withstand a load of at least 100 KNewtons exerted by a loading device, as described in the attached Appendix A, before this loading device travels 400 mm as measured from a vertical plane at the forward-most point of the significant structure of the vehicle.

9. PHASE III: STUDIES FOR FRONTAL COMPATIBILITY IMPROVEMENT

In this phase of the research, focus will be on stiffness matching and passenger car structural integrity. This will pertain to the study of front-end stiffness performance by investigating tests over the next two years to determine appropriate front-end stiffness characteristics and criteria to evaluate small vehicle passenger compartment strength and integrity. The criterion will be to develop a test procedure to enhance partner protection without any significant decrease in self-protection. Test procedures under consideration are load cell barrier tests and vehicle-to-vehicle tests.

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APPENDIX A

Test procedure for Phase II Recommendation for SEAS Conformance to these requirements may be assessed by either of the two procedures below.

Procedure A: Quasi-static Force Application for Evaluating Secondary Structure

1 Definitions

1.1 Secondary Energy Absorbing Structure – SEAS

2 Requirements

2.1 SEAS Location. The SEAS must be connected to the primary energy absorbing structure of the vehicle.

2.2 SEAS Strength. The SEAS must resist the force level specified in S2.2.1 without exceeding the total force application device travel distance specified in S2.2.2.

2.2.1 A minimum force of 100 kN

A maximum horizontal travel of the force application device of 400 mm as measured from the forward-most point of the significant structure of the vehicle. The forward-most point of the significant structure of the vehicle as defined at 3.3.6.

2.3 Secondary Energy Absorbing Structure – SEAS

3 SEAS Test Procedures. The procedures for evaluating the SEAS to the criteria of S2 are specified in S3.1 through S4.0

3.1 Force Application Device. The force application device employed in S3.4 of this section consists of a rectangular solid made of rigid steel. The steel solid is 125 mm in height, 25 mm in thickness. For the measurements, the top edge of the solid shall be placed so that its first contact is only with the SEAS. The width of the solid must be at least the horizontal (y-direction) dimension of the SEAS. The face of the block is used at the contact surface for application of the forces specified in S2.2.1. Each edge of the contact surface has a radius of curvature of 5 mm plus or minus 1 mm.

3.1.1 The solid rectangle of S3.1 shall be rigidly attached to a device capable of applying quasi-static load as specified in S3.4.

3.1.2 Instrumentation with a minimum accuracy of 5 percent plus or minus 5 percent shall be used for measuring the load and will be placed in the force application device so that it measures the actual load being transmitted into the vehicle SEAS.

3.1.3 Travel of the force application shall be measured in a horizontal direction from the point of foremost significant structure on the vehicle, this 'foremost point of significant structure' as defined at 3.3.6.

3.2 Vehicle Preparation. The vehicle should be prepared such that it is secured in the stationary position.

3.2.1 The vehicle must be secured on a rigid, horizontal fixture (± 0.250º) so that it is adequately restrained at the vehicle underbody and also at the sides to prevent rearward movement of the whole vehicle during the test. Good engineering judgment will be required to provide maximum support, for the maximum area possible.

3.2.2 Secure the vehicle in the tie-down fixture as described in S3.2.1. A sufficient number of horizontal and vertical tie-downs shall be used to prevent movement under load. The vehicle may be secured to the loading fixture using wire rope, turnbuckles, strap plates, etc.

3.2.3 An unyielding vertical face shall support the vehicle rear bumper to prevent rearward movement.

3.3 Positioning the Force Application Device. Before applying any force to the guard, locate the force application device such that:

3.3.1 The center point of the contact surface of the force application device is aligned with the SEAS at the vehicle horizontal centerline.

3.3.2 The force application device top edge shall be no higher than 455 mm

3.3.3 The force application device must be vertically positioned so as to insure that the first point of contact during the test is with the SEAS.

3.3.4 If necessary to achieve the condition achieved in S3.3.3, any structure in front of the SEAS should be removed before force application.

3.3.5 The longitudinal axis of the force application device passes through the horizontal centerline of the vehicle and is perpendicular to the vertical axis of the vehicle.

3.3.6 Forward-most Point of Significant Structure: The forward-most point of significant structure on the vehicle is defined as the first point on the vehicle structure that participates in the management of the forces generated in high severity frontal crashes.

3.3.7 Alignment: The front face of the force application device is aligned with the horizontal plane passing through the foremost point of significant structure on the vehicle.

3.4 Force Application: After the force application device has been positioned according to S3.3 of this section, apply the load per the force application procedures described in S3.4.1 through S3.4.2.3.4.1

3.4.1 Rate of Travel: Apply force continuously such that the force application device travel rate does not exceed 12.5 mm per second until the minimum force in S2.1.1 has been exceeded or until the force application device has traveled the total distance in S2.1.2 from the position in S3.3, whichever occurs first.

3.4.2 Direction of Travel: During each force application, the force application device is guided so as to travel only horizontally in a direction perpendicular to the surface of the device during the entire test. At all times during the application of force, the location of the longitudinal axis of the force application device remains constant.

Procedure B: Dynamic Force Application for Evaluating Secondary Structure

4.1 As an alternative, this measurement may be made with a ‘loading attachment’ to a fixed barrier. The vehicle will move into this attachment at the minimum velocity that will result in at least 400mm of horizontal travel by the forward-most point of the significant structure of the vehicle. The movement of the vehicle shall be horizontally in a direction perpendicular to the plane of the loading attachment.

4.2 This attachment shall be designed to perform as the force application device described in S3 for the quasi-static test procedure and will have the same dimensions and instrumentations.

4.3 The test shall be performed by removing as necessary any structure in front of the SEAS (e.g. bumpers, fascias etc) so as to insure that the first point of contact of the loading attachment is with the designated SEAS on the vehicle.

APPENDIX B

**Testing to Support Development
of
Dynamic Test Procedures and Performance Criteria
to Promote Geometrical Compatibility**

F-to-F Compatibility Proposed Tests	**BARRIER TESTS**		**VEHICLE-TO-VEHICLE TESTS**		
	NCAP With 125mmx125mm Load Cell	**TRL Barrier**	**Small Size Pass. Car**	**Mid Size Pass. Car**	**Full Size Pass. Car** As Indicated by Other Test Results
Mid SUV WITHOUT SEAS (Secondary energy absorbing structure)	Physical Tests 50x50 Load cells GM - 2 tests -Jan 15, 04 Simulations DCX GM - complete BMW	Physical Tests GM –2 tests March 1, 04 Explorer (pre-2002) [4900 lbs] Explorer (Current) [4900 lbs] Simulations DCX GM - March 1, 04 BMW	Physical Tests MMC(Japan Spec Veh)	Physical Tests Explorer (Current) - 50% Offset/Collinear [4900 lbs] -Full engagement/ Collinear [4900 lbs]	
Mid SUV WITH SEAS	Physical Tests Honda Toyota (4 Runner) Simulations DCX MMC GM	Physical Tests GM – March 30, 04 Ford Honda Toyota (4 Runner) Simulations DCX MMC GM – March 15, 04	Physical Tests Toyota (4 Runner) Toyota (4 Runner-60mm)		
FULL SUV WITHOUT SEAS	Physical Tests Nissan *Expedition (pre-2003) * [5650 lbs] *Expedition (Current) * [5900 lbs] *50mmX50mm Simulations DCX	Physical Tests Nissan Simulations DCX			
FULL SUV WITH SEAS	Physical Tests Simulations	Physical Tests Simulations		Physical Tests Excursion (Current) - Full engagement/ Collinear [7500 lbs]	
SMALL PICKUP WITHOUT SEAS					
SMALL PICKUP WITH SEAS					

Testing to Support Development of Dynamic Test Procedures and Performance Criteria to Promote Geometrical Compatibility, Cont'd.					
F-to-F Compatibility Proposed Tests	**BARRIER TESTS**		**VEHICLE-TO-VEHICLE TESTS**		
	NCAP With 125mmx125mm Load Cell	**TRL Barrier**	**Small Size Pass. Car**	**Mid Size Pass. Car**	**Full Size Pass. Car** As Indicated by Other Test Results
MEDIUM PICKUP WITHOUT SEAS	Simulations DCX (1500 Series)	Physical Tests F150 (Current) [5200 lbs] F150 (2004) [5800 lbs] Simulations DCX (1500 Series			
MEDIUM PICKUP WITH SEAS	Simulations DCX (1500 Series)	Simulations DCX (1500 Series)			
LARGE PICKUP WITHOUT SEAS	Physical Tests GM – 2 Tests completed Simulations DCX (2500 Series) GM – completed	Physical Tests Ford Simulations DCX (2500 Series) GM – April 30, 04			
LARGE PICKUP WITH SEAS	Simulations DCX (2500 Series)	Physical Tests F250 (Current) [7400 lbs] GM – April 30, 04 Simulations DCX (2500 Series) GM – April 30, 04			
LARGE SEDAN	Physical Tests	Physical Tests			
SMALL SIZE CAR	Physical Tests Honda	Physical Tests Honda VW	NA	NA	NA
MID SIZE CAR	Physical Tests Honda	Physical Tests VW Honda	NA	NA	NA

PASSENGER VEHICLE CRASH TEST PROCEDURE DEVELOPMENTS IN THE VC-COMPAT PROJECT

Robert Thomson
Chalmers University of Technology
Sweden
Mervyn Edwards
TRL, Limited (Transport Research Laboratory)
United Kingdom
on behalf of the VC-Compat Consortium
Paper Number 05-0008

ABSTRACT

The project "Improvement of Vehicle Crash Compatibility through the development of Crash Test Procedures" (VC-Compat) is a research activity sponsored under the European Commission 5th Framework Programme. It consists of two parallel research activities, one focusing on car-to-car* compatibility and the other on car-to-truck compatibility. The main objective of the car-to-car research is the development of crash test procedures to assess frontal impact crash compatibility. The car-to-truck objective is to develop test methods to assess energy absorbing frontal underrun protection for trucks.

The midterm project status of the car-to-car work program is reported in this paper. A survey of European passenger vehicles has been conducted to construct a database of common crashworthiness structures. A review of the detailed accident databases in Germany and UK has been used to identify a target population of accident victims that could benefit from improved vehicle compatibility. Testing and modelling activities have been conducted to improve the understanding of the relationship between crash behaviour in the candidate test procedures and car-to-car crashes. These research activities are helping to develop and evaluate candidate test procedures. To date, work has focused on the Full Width Deformable Barrier (FWDB) and Progressive Deformable Barrier (PDB) tests, which use two different approaches to assess a car's compatibility. The FWDB test uses load cell wall force measurements whereas the PDB test uses barrier deformation measurements. The activities described herein will continue throughout the project and lead to draft test procedures with performance criteria and limits.

* The car definition includes SUVs.

INTRODUCTION

Following the introduction of the European frontal and side impact Directives and EuroNCAP†, car safety has made a major step forward. Even so, there are still over 38000 fatalities and 1.6 million injured people due to traffic accidents in Europe [1]. Passive safety equipment operates well under idealized crash test conditions. However, behaviour of car structures and safety systems during real world conditions is not always directly comparable to crash tested behaviour, especially in car-to-car crashes. The next step to further improve frontal impact protection is to improve compatibility. Crash compatibility will ensure that car frontal structures are more effectively utilized in car-to-car collisions. This should help reduce compartment intrusion in severe accidents and thereby lead to a decrease in the number of serious and fatal injuries.

Compatibility is a complex issue but can be broken down into three subtopics: structural interaction, frontal force levels and compartment strength. Structural interaction is a measurement of how well vehicles interact in frontal impacts. If the structural interaction is poor, the energy absorbing front structures of the vehicle may not function as designed leading to a risk of compartment intrusion at lower than designed impact severities. In general, frontal force levels are currently related to vehicle mass[2]. As a consequence, small vehicles absorb more than their share of the impact energy as they are unable to deform the heavier vehicle at the higher force levels required. Matched frontal force levels would ensure that both vehicles in an impact absorb their share of the kinetic energy. This would reduce the risk of injury for the occupant in the lighter vehicle. Compartment strength is closely related to frontal force levels but is nevertheless distinguished since it is such an important issue for self-protection. In cases where the vehicle front structures do not absorb the amount of energy as designed - or in cases where the vehicle is exposed to higher impact severity than it is designed for - the compartment strength needs to be sufficiently high to resist a compartment collapse.

VC-Compat[3] is a 3-year project, part financed by the European Commission which started in March 1st 2003 and is split into two research legs; a car-to-car

† EuroNCAP is the European New Car Assessment Programme which provides the consumer with car safety ratings

leg and a car-to-truck leg. Both legs follow separate research plans with defined points of interaction and information exchange. It is the car-to-car leg consisting of research partners from the UK, France, Germany, Sweden, Italy, and the Netherlands, that is reported in this paper. The scientific and technical objectives for car-to-car research are:

- to develop a suite of draft test procedures and associated performance criteria outlines to assess and control car frontal structures for frontal impact compatibility.
- to ensure that the number of additional test procedures is minimised to keep the test burden on industry to a minimum.
- to provide general recommendations for the design of a compatible car.
- to provide an indication of the benefits and costs of improved compatibility.

European Enhanced Vehicle-safety Committee (EEVC) Working Group 15 members and their industrial advisors are acting as a technical steering group for VC-Compat project to ensure that appropriate test procedures are developed. Project results are also reported to the International Harmonised Research Activities (IHRA) compatibility working group to obtain a world-wide perspective. Recently, the EEVC WG15 has defined a route map to improve frontal impact compatibility. The general objectives of the route map are to:

- Address partner and self protection without decreasing current self protection levels.
- Keep number of procedures to a minimum.
- Internationally harmonise procedures.

The short term objectives are to develop requirements to:

- Improve structural interaction.
- Ensure that frontal force mismatch (stiffness) does not increase and compartment strength does not decrease from current levels.

The medium term objectives are to develop requirements to:

- Improve compartment strength, especially for light vehicles.
- Take first steps to improve frontal force matching.
- Further improve structural interaction.

These objectives are in line with the compatibility route map proposed by the European automotive industry

CANDIDATE TEST PROCEDURES

As a result of previous research work by manufacturers and governments, outlines of 4 possible test procedures were proposed as a starting point for the VC-COMPAT work:

- Full width Deformable Barrier (FWDB) test at 56 km/h to assess structural interaction.
- Progressive Deformable Barrier (PDB) test at 60 km/h to assess structural interaction and frontal force levels.
- Offset Deformable Barrier (ODB) test at 64 km/h to assess frontal force levels.
- High speed Offset Deformable Barrier (ODB) test at 80 km/h to assess compartment strength.

The FWDB test has a deformable element and uses measurements from a high resolution load cell wall (LCW) to assess a car’s structural interaction potential and has been described previously[4]. The premise is that cars exhibiting a more homogeneous force distribution on the LCW should have a better structural interaction potential. Two metrics to assess a vehicle’s structural interaction potential have been proposed: the homogeneity criterion and the Average Height of Force (AHOF). The development of the homogeneity criterion metric has been described previously[2]. It is based on the difference between peak cell loads and an ideal (or target) load level over a specified assessment area or footprint and has cell, vertical and horizontal components. To address a mass dependency problem, the homogeneity criterion was recently ‘normalised’. The new criterion is called the relative homogeneity criterion and is calculated by dividing the homogeneity criterion by the target load squared. The AHOF is a single value representing a force weighted average of the centre of force on the LCW above ground level throughout the impact [5].

The PDB test is a 50 percent overlap offset test which uses measurements from a progressive deformable barrier to assess a car’s compatibility [6]. The barrier stiffness increases with depth and has upper and lower load levels to represent an actual car structure. The progressive stiffness of the barrier has been designed so that the Equivalent Energy Speed (EES) for the vehicle should be independent of the vehicle’s mass. The reader is referred to [7] for more information on the PDB barrier performance.

The PDB assesses both a car’s structural interaction potential and frontal force level in the same test. Laser scanning techniques are used to measure the 3D barrier deformations. The development of the PDB metrics is reported separately[7]. The first of these is the Partner Protection Assessment Deformation

(PPAD) which is a measure of the car's aggressivity. The formula for calculating the PPAD metric is:

$$PPAD = \sum_{i=1}^{14} S_i \left(\frac{Z_i}{Z_{\lim}} \right)^4 \left(\frac{X_i}{X_{\lim}} \right)^2 \qquad (2).$$

where: i is the index for reference depths (14 ranges in the current proposal); Z_{lim} and X_{lim} are the limit values for barrier deformations in the vertical and longitudinal directions respectively; S_i is the surface area for a range of deformation depths: Z_i and X_i are the average depth and height for each surface area

In addition to the PPAD, the Average height of Deformation (AHOD) - comparable to the AHOF in load cell wall tests - and the Average Depth of Deformation (ADOD) metrics are available. All of these metrics are based on the longitudinal and vertical deformation pattern of the barrier face. In principle, the uniformity of the barrier deformation gives a measure of the vehicle's structural interaction potential and the longitudinal barrier deformation indicates its frontal force levels.

The use of the 64 km/h Offset Deformable Barrier (ODB) test to measure force has been described previously[4]. It aims to assess a car's frontal force levels from a measurement of the peak force from a LCW positioned behind the deformable element.

The high speed ODB test has also been described previously[4]. It aims to ensure that a car's compartment strength exceeds a minimum requirement, so that it is able to withstand the forces imposed by another car.

EEVC WG16 have recommended the use of both an offset and a full width test for assessing a car's self protection capability in frontal impact to ensure that the car is not optimised to one particular crash configuration. Ideally, to keep the number of test procedures to a minimum, current frontal impact tests should be adapted to include compatibility measures. For example current FMVSS208 type tests could be adapted by adding a deformable element and a LCW to form the FWDB test and the current European offset test could be adapted by changing the barrier face to form the PDB test. It should be noted that the French have recently proposed that the barrier face in the ECE regulation 94 test should be replaced by the PDB face for self protection reasons. The use of a PDB barrier should harmonise the test severity among vehicles of different masses and encourage lighter vehicles to be stronger. The second stage for this proposal is the introduction of compatibility assessments after they are validated[7].

Two proposals for combining the candidate tests to form a suite of test procedures to assess frontal impact protection and compatibility have been made. The first is the FWDB test, the offset deformable barrier (ODB) test and the high speed ODB test[4]. The second is the PDB test and a full width rigid wall test[7]. At this stage the best combination of tests still has to be determined and it could include both the FWDB and PDB tests.

VC-COMPAT WORK PROGRAM

There are four activities that provide the technical basis for the research:

- **A structural survey** to create a database of positions and dimensions of the important energy absorbing structures in vehicles. This will be used to determine appropriate structural interaction areas for vehicles.
- **Accident analysis** to estimate the benefit and cost of improved compatibility.
- **A crash testing program** of car-to-car and car-to-barrier crash tests to validate the crash test procedures and develop appropriate performance criteria.
- **Mathematical modelling** to support the development of the test procedures and the cost benefit analysis.

The results of these four activities will be brought together in another activity to synthesize the crash test procedures. In addition, a dissemination activity is communicating the results and findings from this project and soliciting input from industry.

Structural Survey (Leader: UTAC)

There are two structural properties that determine a vehicle's "aggressivity" to its opponent: physical strength (or stiffness) of the vehicle components and the position of these components. The first property is associated with the frontal force level compatibility and the second describes a geometric compatibility. The objective of the structural survey was to measure and create a database of the position and dimensions of vehicle structures involved in frontal and side impact. This database will be used to study current geometric compatibility.

The specific tasks undertaken were to:

- Define the main vehicle structures involved in frontal and side car-to-car impacts.
- Define a representative group of vehicles for measurement.
- Measure the vehicles and generate the database.
- Analysis of the database to determine suitable interaction areas for car-to-car impacts.

A measurement procedure was developed by the group using the results of previous activities [8]. The structural database contains the following information:

- General information of the vehicle (model, engine and subframe type, mass, length, etc.).
- The front unit measurement (position of bumper, engine, subframe, lower rail, crush can, footwell, etc.).
- Side unit measurement (A, B and C pillar, position of floor sills, fender, etc.).

The 55 cars in Table 1 have been measured with the goal to have cars from different segments and car manufacturers in order to get a good average of the European fleet. This selection represents 61% of the European sales in 2003.

Information contained in the structural database has been helpful to understand the results obtained in car-to-car and car-to-barrier testing. The database provides the positions of the main frontal structures which must engage in car-to-car impacts to ensure good structural interaction. A typical analysis is shown in Figure 1 where the vertical position of the vehicle structures can be described in terms of the maximum, minimum, average, and weighted average values. Similar analyses for the lateral position and sectional dimensions can be conducted.

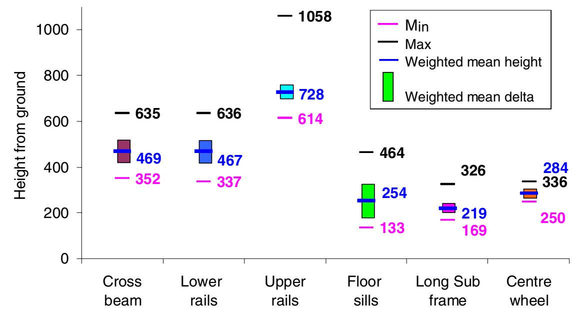


Figure 1: Vertical positions of significant structural components

This survey provides useful data for developing an assessment area for compatibility test procedures. For example, an assessment area would have encompass a vertical range between about 180 mm and 800 mm to include the subframe, main rail, upper rail and wheel sill load paths.

Table 1. Vehicles selected for structural survey

A segment	**B segment**	**C segment**	**D segment**	**D/E segment**
1- Citroën C2 2-Renault Twingo 3- Smart 4- Toyota Yaris 5- Citroën Saxo	6- Citroën C3 7- Opel Corsa 8- Renault Clio 9- VW Polo 10- Peugeot 206 11- Fiat Punto 12- Ford Fiesta 13- Seat Ibiza 14- Mercedes Aclass	5- PT Cruiser 16- Ford Focus 17- Opel Astra 18- Peugeot 307 19- Renault Megane 20- Audi A3 21- BMW 3 series 22- VW Golf 23-Mercedes C class 24- Fiat Stilo	25- Saturn Ion 26- Ford Mondeo 27- Mazda 6 28- Opel Vectra 29- Renault Laguna 30- Rover 75 31- VW Passat 32- Audi A4 33- Citroën C5	34- Mercedes E Class 35- Renault Velsatis 36- Volvo S80
F segment	**Small MPV**	**MPV**	**4WD**	**LCV**
37- BMW 7series 38- Mercedes S Class 39- VW Phaeton	40- Opel Meriva 41- Citroën Picasso 42- Opel Zafira 43- Renault Scenic 44- VW Touran 45- Renault Kangoo	46- Citroën C8 47- Renault Espace 48- VW Sharan	49- Honda CRV 50- Nissan Xtrail 51- Freelander 52- Volvo XC90 53- Range Rover	54- Renault Traffic 55- Ford Transit

Accident and Cost Benefit Study (Leader: BASt)

The objective of WP2 is to determine the benefits and costs of improved compatibility for frontal impact. As a first step, the available accident data was reviewed and analysed to identify a "target population" for improved compatibility. The target population was defined as those casualties who are likely to experience a reduced risk of injury as a result of the implementation of improved compatibility measures.

To determine the target population it was necessary to identify the accidents in which improved compatibility measures were judged to reduce the risk of injury to the occupant. Since it is impossible to precisely identify the accidents where compatibility measures would have helped, selection criteria to give upper (optimistic) and lower (pessimistic) bounds were used. Examples of the selection criteria used are shown in Table 2. Following this, the casualties that occurred in the selected accidents were counted to give upper and lower bounds to the target population.

Table 2: Accident configuration selection criteria for estimation of target population

Selection Criteria	Optimistic Limit	Pessimistic Limit
Vehicle overlap	overlap > 20	overlap > 30
PDOF	10-2 o'clock	11-1 o'clock
Equivalent Energy Speed	All impacts under 56 kph EES + 50% of impacts 56 <EES<80 kph	All impacts under 48 kmh EES +50% of impacts 56 <EES<80 kph
Delta V	All values	Delta v < 56 kph
Heavy Vehicle Underrun	Include all underrun cases	Include 80% underrun cases
Belt Restraint System Use	Only restrained occupants	Only restrained occupants
Occupant Seating Position	Only front seat occupants	Only front seat occupants

Detailed analyses of the German In Depth Accident Study (GIDAS) database and the UK Cooperative Crashworthiness Injury Study (CCIS) database have been carried out by BASt and TRL, respectively. For Germany, the target population was estimated to be between 14% (611) and 21% (916) of fatally injured car occupants and between 29% and 39% of seriously injured car occupants, annually. For Great Britain, the target population was estimated to be between 20% (343) and 31% (543) of fatally injured car occupants and between 41% and 52% of seriously injured car occupants, annually.

Any potential influence of frontal impact compatibility on side impact situations was not considered in this study.

Even though the consequences of frontal impacts have been substantially moderated by recent safety developments, the analyses showed that the frontal impact category still plays an important role (40 to 50 percent of all car occupant fatalities and 60 to 70 percent of seriously injured car occupants). Although the distribution of impact partners (i.e. trees, cars, HGVs, etc.) for cars are quite different in various European countries, compatibility shows some universal usefulness. It does not only have influence in car-to-car accidents but also considerable influence in accidents with roadside obstacles and other objects. More homogenous front structures should lead to a better interaction with both wide and narrow objects.

The results of the German and British in-depth data analyses (mentioned above) were used to extrapolate the target population to the European level This estimation was based on CARE[1] and IRTAD[9] data for the year 2000, representing about 24,759 fatal car occupants a year for the EU-15 members. It is impossible to find the number of seriously injured car occupants with the current databases (CARE, IRTAD etc.). Therefore, the approximation that there are 7 seriously injured per 1 fatality injured individual was used. Therefore for 24,759 fatal car occupants, 173,313 seriously injured occupants were calculated. These numbers do not account for any other safety effects, for instance side impact protection or more effective restraint systems. They do, however, account for the low seatbelt usage rate in some European countries.

Using the European numbers for annual road traffic trauma victims and scaling the target populations identified in German and UK data analyses, the following upper and lower boundary estimates were made:

- about 3,466 (14%) to 7,675 (31%) fatally injured car occupants are within the Compatibility Target Population
- about 50,260 (29%) to 90,122 (52%) seriously injured car occupants are within the Compatibility Target Population

The development of methodologies to estimate the benefit of improved car frontal impact compatibility (including modelling approaches) is in progress.

Crash Testing (Leader: TRL)

The objective of the crash testing activity is to perform full scale crash tests and associated analyses to help develop and validate a suite of test procedures to improve car frontal impact compatibility. The following candidate test procedures formed the starting point for this work:

- Full Width Deformable Barrier (FWDB) test at 56 km/h to assess structural interaction.
- Progressive Deformable Barrier (PDB) offset test at 60 km/h to assess structural interaction and frontal force levels.
- Offset Deformable Barrier (ODB) test at 64 km/h to assess frontal force levels.
- High speed Offset Deformable Barrier (ODB) test at 80 km/h to assess compartment strength.

The work performed has mainly focused on the development of tests that can assess a car's structural interaction potential, the FWDB and PDB test procedures. This follows the EEVC WG 15 route map which, in the short term, requires a test to assess structural interaction. Also, previous research has shown that good structural interaction is an essential prerequisite for compatibility [10]. Load cell wall (LCW) data has been collected from selected EuroNCAP tests to further develop the 64 km/h ODB test. To date, no effort has been directed at the development of the high speed ODB test to assess compartment strength.

Previous research[4] has shown that to achieve good structural interaction, it is important that the structures of each car meet suitable components on the other car to react against. Current views are that this is best achieved by utilising multiple level load paths with good links between them. These reasons led to the current FWDB and PDB assessment criteria which encourage a design with good vertical load spreading capabilities, i.e. a multiple level load path design. However, it is still not known whether good predictable structural interaction over the full range of real world impact conditions could be achieved with the current generation one-level load path car design, i.e. lower rails only.

Car-to-car tests were performed to address this fundamental question and provide data to validate the FWDB and PDB test procedures. These tests were performed with identical cars to keep parameters such as the car's frontal force level and compartment strength constant to ensure that only the car's structural interaction behaviour could affect the test outcome. Tests were performed with a 50 percent overlap, a closing speed 112 km/h, and a ride height difference of 60 mm between the cars to emphasize the effect of any over/underride that might have occurred. The results from two tests are reported. Both tests used modern design small family cars having good self protection (a 5 star EuroNCAP rating). The first test used a one-level load path design car (main rails only) with a mass of 1507 kg (Car 1), and the second test was a two-level load path design (main rails and engine subframe) with a mass of 1402 kg (Car 2).

For the test with the one-level load path car, Car 1, significant under/override was observed. The main rail of the lower car bent down substantially and the rail of the higher car bent up (Figure 2).

For the test with the two-level load path car, Car 2, less over/underride was observed. There was less vertical movement of the main rails even though the vertical connections between main rails and engine subframe failed (Figure 3). From detailed examination of the vehicles it is believed that under/override occurred at the beginning of the impact but it was limited by the interaction of the front impact side wheel and the subframe of the opposing car.

To judge the structural interaction performance of the cars in these tests, a comparison to a benchmark test was made. The benchmark test used was a 64 km/h ODB test because the EES of each car in this test and a car-to-car test with a 50 percent overlap and a closing speed of 112 km/h are approximately equal. A car's deformation mode behaviour should be best in the 64 km/h ODB test because cars are, in general, designed for optimum performance in this test. When the performances of the cars in the car-to-car tests were compared to those in the benchmark test, it was seen that the performances of the two-level load path cars were closer to the benchmark. This is illustrated by a comparison of compartment deformation measures, in particular the A pillar movement and door aperture closure (Figure 4). This result indicates that the structural interaction performance of the two-level load path car was better than a single level load path design. This supports the argument to have a metric that encourages the design of cars with good vertical load spreading capabilities. Further test and FE modelling work is planned to confirm this conclusion.

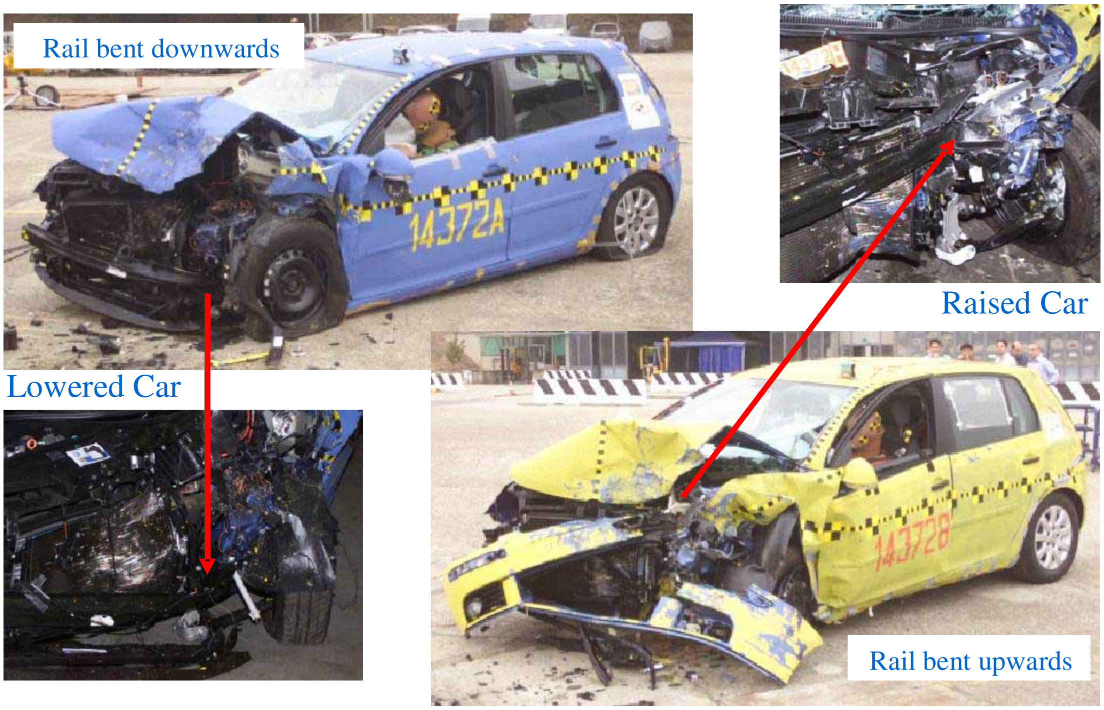


Figure 2: Car-to-car test with single load path level cars (Car 1): Note over/underriding

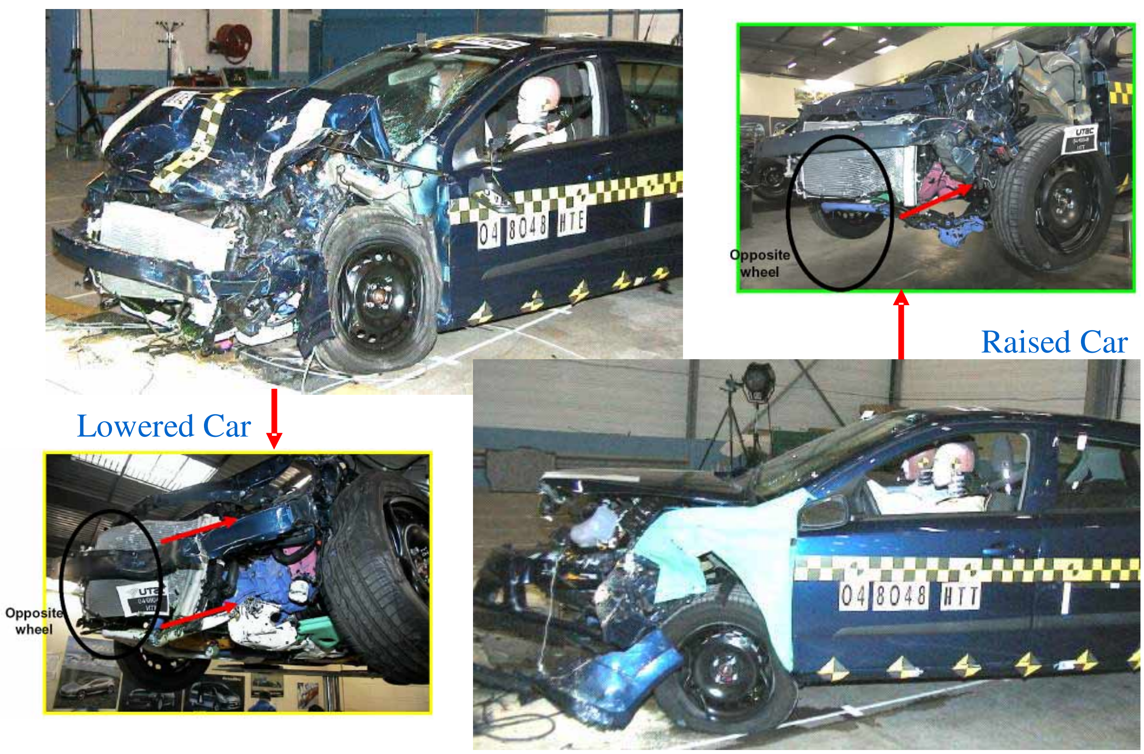
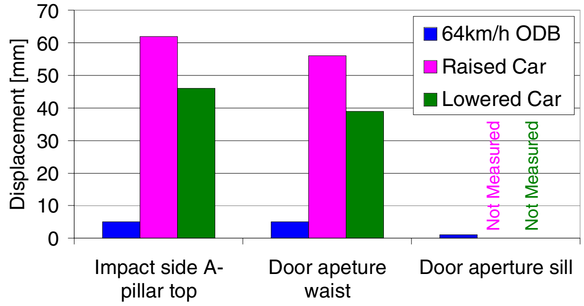
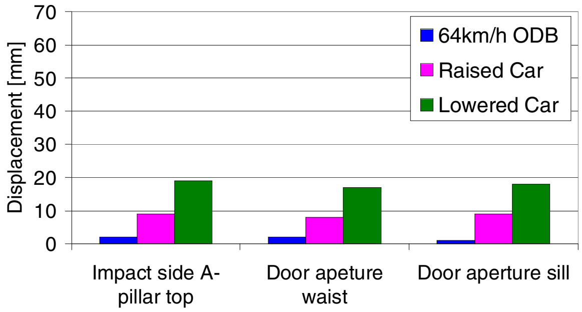


Figure 3: Car-to-car test with two load path levels cars (Car 2): Note contact of wheel with subframe



Car 1

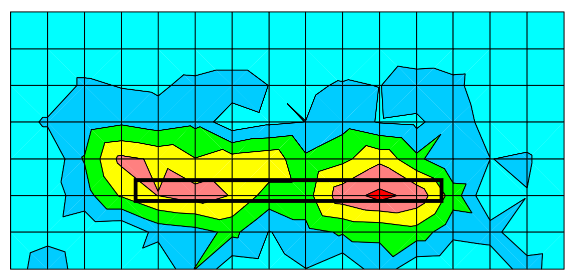


Car 2

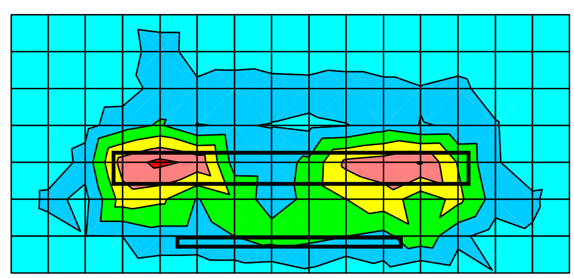
Figure 4: Comparison of the door aperture intrusions between the car-to-car tests and 64 km/h ODB tests

Car 2

Figure 5: Vehicle Deformations from FWDB Tests: Note different cross beam deformation for the cars



Car 1



Car 2

Figure 6: Load Cell Wall Force Contours in FWDB Test: Note the influence of the subframe for Car 2

__FWDB tests have been performed__ with a range of vehicles including Car 1 and Car 2. The post test deformations of Car 1 and Car 2 are shown (Figure 5). The main difference to note is that Car 2's bumper crossbeam failed in bending at its centre which was not the case for Car 1. This indicates that the crossbeam in Car 1 is better able to spread the load from the main rail than Car 2's crossbeam.

The FWDB assessment is based on the load cell wall (LCW) force distribution. The LCW peak cell force distributions for Car 1 and Car 2 are shown (Figure 6). It is apparent that Car 1's bumper crossbeam gives a more uniform force distribution laterally across the wall with higher loads at its centre point than Car 2's crossbeam. This indicates Car 1's stronger crossbeam performance. For Car 2, forces are better distributed between the main rails and the subframe position. Note that the subframe of Car 2 bent upwards during the crash from its static position indicated in Figure 6.

Two metrics are currently available for the FWDB test, the relative homogeneity criterion and the Average Height of Force (AHOF). The relative homogeneity criterion is shown for the range of vehicles tested, plotted in order of increasing mass (Figure 7). It consists of three components, which indicate how well the load is distributed globally over the wall (cell), distributed vertically (row), and horizontally (column).

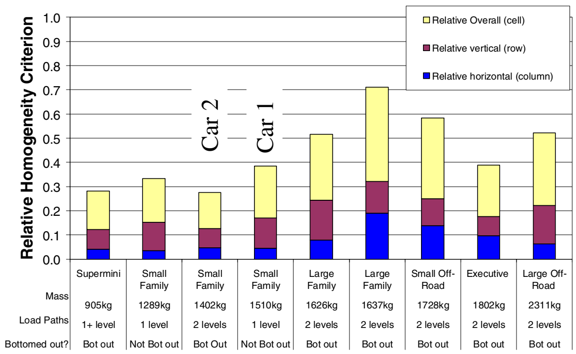


Figure 7: Relative Homogeneity Criteria Plotted Against Increasing Vehicle Mass

It is seen that Car 2 had a better relative homogeneity score than Car 1, (0.28 cf 0.39) indicating that it spread its load more uniformly on the wall than Car 1. This difference was greater for the vertical component (0.08 cf 0.12) which is expected as Car 2 has a two-level load path design and in principle should be better able to spread its load vertically. In general, it might be expected that cars with multiple-level load path designs should spread their load vertically better and hence achieve a better vertical relative homogeneity component score. However, if the full data set is examined the vertical component of the relative homogeneity criterion does not appear to clearly distinguish between the cars with one-level of load path and those with more. This is not unexpected as it is unlikely that a simple subjective count of a car's load path levels is a good measure of its vertical load spreading capability and structural interaction potential. Further car-to-car test validation data is required to investigate this issue fully.

The AHOF is shown in Figure 8 for the range of vehicles tested, plotted for increasing vehicle mass, including Car 1 and 2. It is seen that Car 1 records a higher AHOF value than Car 2 which, at first sight, is unexpected as Car 2 has a subframe load path which applies load at a low height on the wall. However, it should be noted that the Car 1 has a lower bumper crossbeam than Car 2 which could explain this apparent anomaly.

Figure 9 is a graph of the peak total LCW force plotted against vehicle mass. It is seen that the total LCW force peak increases with increasing vehicle mass indicating that heavier vehicles have higher frontal force levels. Although the primary aim of the FWDB test is to assess a vehicle's structural interaction potential it may be possible to use this test to a vehicle's frontal force levels in a similar way to that proposed for the 64 km/h ODB test. Further work is needed to investigate this issue.

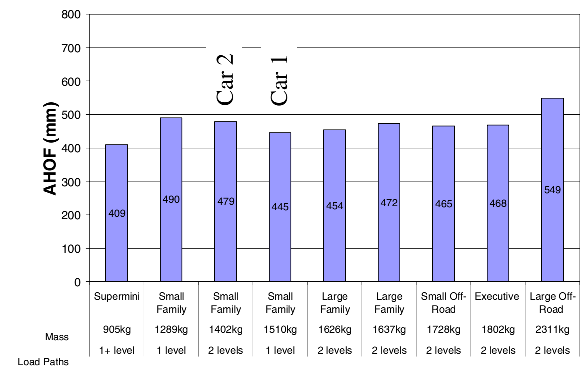


Figure 8: AHOF Results from FWDB

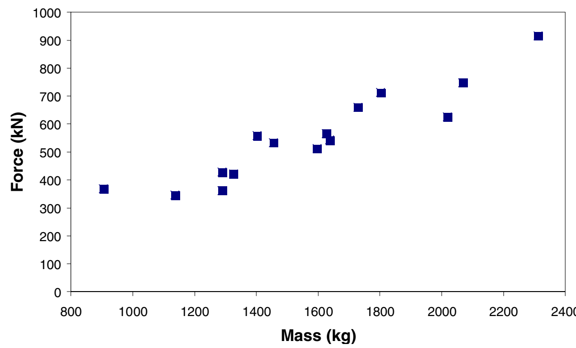


Figure 9: Peak LCW force measurement for FWDB tests.

PDB assessment is based on the barrier deformation. The barrier deformations from the tests with Car 1 and Car 2 are shown in Figure 11 together with contour plots obtained from laser scanning of the barriers (Figure 12). Greater barrier face deformation is seen at subframe level for Car 2 than Car 1 indicating that the subframe load path on Car 2 was detected. For Car 2 there was a high localised deformation in alignment with the main rail load path caused by the failure of the bumper crossbeam, which was not present for Car 1. This shows that the difference in crossbeam performance was detected by the PDB barrier.

Three metrics are currently available for the PDB test, the PPAD, AHOD and ADOD. For each of the PDB metrics, the same vehicles are shown as for the FWDB metrics so that the reader can compare the assessment of the vehicles by the two test methods. The PPAD is a measure of a vehicle's aggressiveness and is shown for the range of vehicles tested including Car 1 and Car 2 (Figure 13). Note that lower PPAD scores are desirable.

The PPAD values for Car 1 and Car 2 are similar. This is not unexpected as the PPAD is a combined measure of a vehicle's structural interaction potential and its frontal force level. Future work will develop a new metric to assess a vehicle's structural interaction potential alone.

The AHOD is shown for the range of vehicles tested (Figure 14). This metric is based on a similar concept to the AHOF metric used for FWDB test. It is seen that Car 1 records a higher AHOD than Car 2 which is expected as Car 2 has a subframe load path. In contrast the AHOF values in the FWDB test were higher for Car 2 than Car 1. However, it should be noted that comparisons between the AHOF and AHOD may not be that meaningful as they have several fundamental differences, for example the AHOF metric is calculated from a force measurement throughout the period of the impact whereas the AHOD metric is calculated from time independent deformation measures.

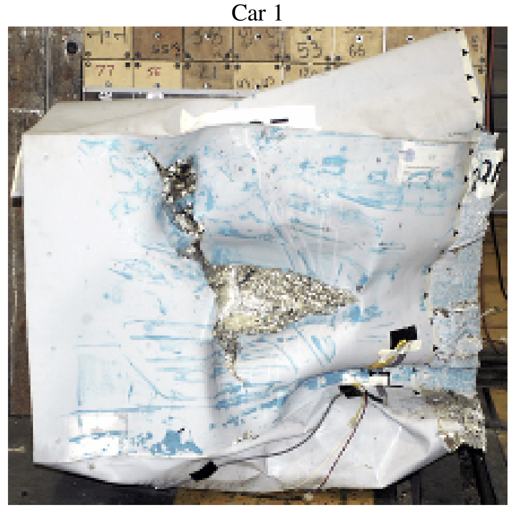
Car 1

Car 2

Figure 10: Vehicle Deformations from PDB Tests: Note different cross beam deformation for the cars

The ADOD is shown for the range of vehicles tested in Figure 15. In general, it is seen that the ranking of the vehicles with this metric is similar to the PPAD metric with the large off-road vehicle having a high score. This is most likely caused by a combination of its high frontal force level and its high structure. Car 1 and Car 2 have similar ADOD values indicating that they have a similar frontal force level.

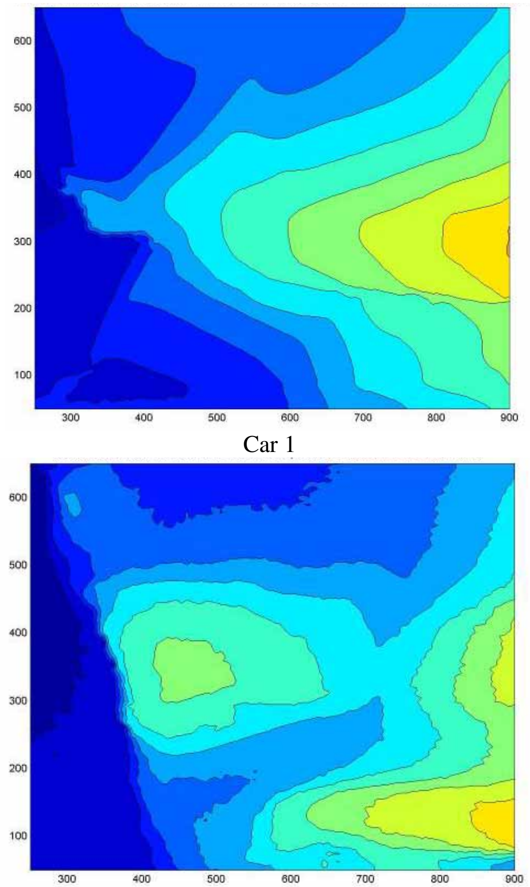
Car 1



Car 2

Figure 11: PDB Barriers Deformation: Note subframe and lower rail imprint for Car 2

<u>In summary</u>, car-to-car testing has shown that the structural interaction performance of a two-level load path car was better than a one-level load path vehicle which supports the use of assessment criteria that encourage car design with good vertical load spreading capability. The FWDB and PDB test tools have been shown to be capable of distinguishing the presence of a subframe load path and the different bumper crossbeam behaviour. The proposed FWDB and PDB assessment criteria have been calculated and compared for a range of vehicles, including the one-level and two-level load path cars. At this stage it appears that both the FWDB and PDB criteria require further development. However, it is not possible to draw definite conclusions because of lack of car-to-car test validation data. Future work is planned to address these issues.



Car 1

Car 2

Figure 12. Barrier Deformation Contours: Note imprint of subframe and lower rail from Car 2

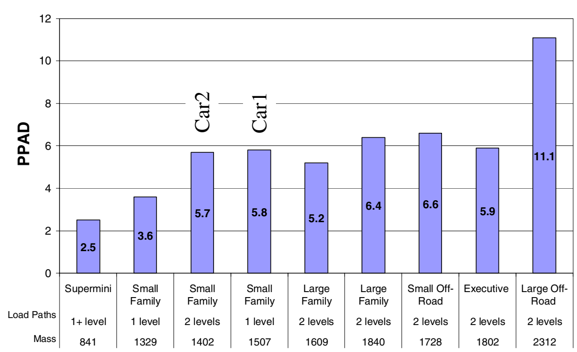


Figure 13: PPAD Test Results Plotted Against Increasing Vehicle Mass

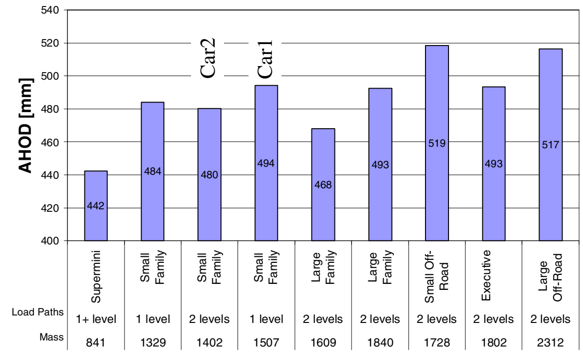


Figure 14: PDB Results for AHOD

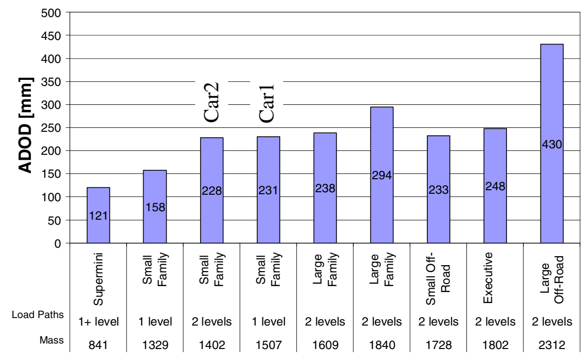


Figure 15: PDB Test Results ADOD

Mathematical Modelling (Leader: TNO)

There were three main computer simulation tasks in the VC-Compat project.

1. Finite Element (FE) barrier modelling to support the development and initial validation of the test procedures
2. Multi-Body (MB) modelling methodology to develop a fleet model to support the benefit estimation and determine the effect of improved compatibility in other crash configurations
3. Multi-body simulation of vehicle force levels to identify strategies for force matching of vehicles with different masses and the consequences for occupant protection

Finite Models were developed to support development of the FWDB test. A FE model in RADIOSS was created by TRL based on NHTSA's LS-Dyna model. The main advantage of this newer model is that there is a capability to simulate local tearing of the honeycomb material by a stiff car structure. To achieve this, the barrier model was constructed from columns of 'standard' type honeycomb elements which were joined by thin 'tear' type honeycomb elements. The ‘tear’ type elements have strain based failure criteria that delete the element when a prescribed strain is reached.

This FWDB model was used in a parametric study to identify the sensitivity of the homogeneity criteria to the alignment of a one-level load path vehicle with the load cell wall. The results of the study showed that changing the impact alignment 62.5 mm horizontally (half a load cell) changed the homogeneity by less than 10%. However, changing the impact alignment 62.5 mm vertically changed the homogeneity by about 30%. It has been estimated that a vertical alignment tolerance of the order +/- 10mm will probably be required to ensure acceptable test repeatability when assessing vehicles that do not spread their load well vertically. Because of this, it is important that the alignment of the vehicle with the wall in each test is recorded.

A fleet model, the second part of modelling activities in VC-Compat, was developed to support the benefit estimation and determine the effect of improved compatibility in other crash configurations. For this purpose, TNO developed a MB vehicle fleet model based on of 7 vehicle models representative of a real life car fleet[2].

The objective of the fleet studies was to develop strategies for evaluating of front-end structures which minimise the total harm in car-to-car crashes. For part of this study, multi-body models were constructed from existing finite element models. Front-end structures and passenger compartments were modelled in detail to provide realistic deformation modes. Furthermore dummies, airbags, belts and main interior parts like dashboard and steering wheel were included. Table 3 gives an overview of the available models. By simulating impacts between different combinations of vehicles, a representation of real life accidents can be made. Figure 16 shows how the models fit into the overall benefit estimation.

A large set of simulations was performed (over 5000 runs) to simulate the reference fleet performance. A second fleet was created where the two smallest vehicles were modified to improve compatibility. Simulations of the second fleet were performed and compared to the results from the reference fleet.

To create an approximation of real world collisions, the accident variables ‘impact velocity’ and ‘impact overlap’ were varied. The initial velocity of each vehicle was within a range of 20-80 km/h and the overlap was varied in a range of 25-80% of the smallest vehicle. The distribution of the variations was set up with the Latin Hyper Cube algorithm implemented in ADVISER©, resulting in 100 batches that randomly generated an even distribution over a given window for a relatively small number of samples.

Figure 17 shows the mean overall injury (ISS) values for all drivers in all scenarios. Especially for the small vehicles (GE, NE) the drivers suffered relatively high injury in collisions with the larger vehicles in the fleet. Improvements to the vehicle compatibility led to lower mean overall injuries for these particular cases.

Table 3 Available multi-body vehicle models for fleet studies

Model	Class	Mass [kg]	Test Mass [kg]
Geo Metro (GE)	Subcompact	900	1191
Chrysler Neon (NE)	Compact pass.	1085	1371
Ford Taurus (TA)	Mid size pass.	1488	1728
Honda Accord (AC)	Mid size pass.	1396	1636
Dodge Caravan (CA)	Full size MPV	1682	1934
Ford Crown Victoria (CV)	Large pass.	1836	2076
Ford Explorer (EX)	SUV	1971	2205

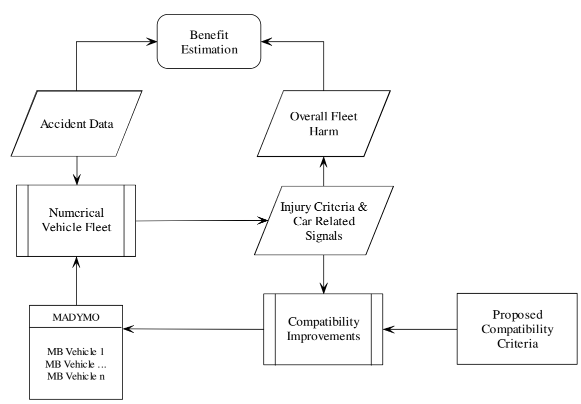


Figure 16: Fleet Systems Model Methodology to Predict Benefit of Proposed Compatibility Criteria.

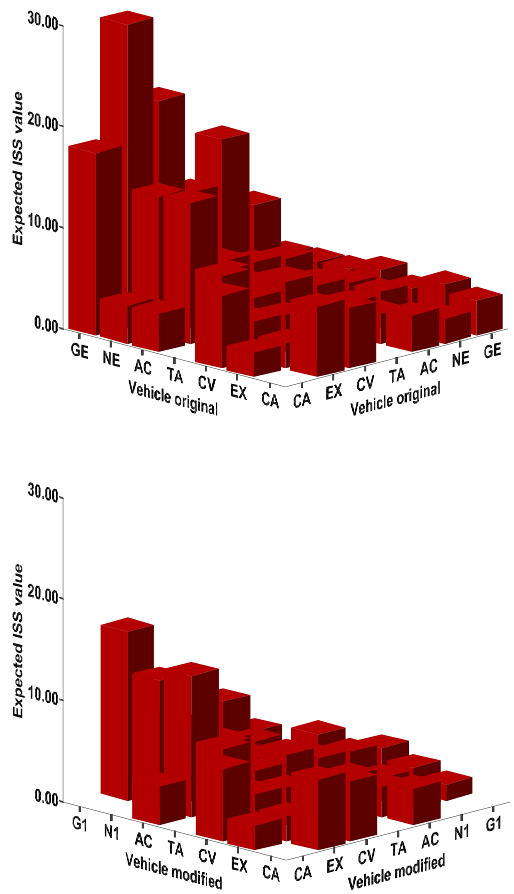


Figure 17: ISS distribution (mean values) for entire subset plotted as function of Target and Bullet car.

A study of frontal force levels was the third activity undertaken in the modelling work package. The objective of this research was to investigate the dependency of frontal force level on vehicle mass in current and future tests. In addition, the influence of the crash pulse on the occupant response must be identified so that no undesirable side effects of the test procedures arise.

This research produced generic vehicle descriptions to model a range of car-to-car collisions. The goal was to find how the stiffness of vehicles could be modified so that impacts involving vehicle pairs with reasonable mass ratios could still result in survivable crash environments. This was investigated by first increasing the stiffness of smaller vehicles (under 1500 kg) from their current levels. The next step for this investigation was to lengthen the existing deformation zones of larger vehicle and study the new range of stiffness levels required for small vehicles under this new traffic condition. The baseline assumption was that all vehicles had the same deformation zone of roughly 700 mm[2].

The results of this preliminary study of vehicle stiffnesses suggested that smaller vehicles can be made stiff enough to provide suitable safety levels in high mass ratio impacts. The increased stiffness resulted in higher accelerations for the smaller vehicles, but impacts with mass ratios 1:1.6 were survivable with appropriate safety equipment designs. A similar result was found for the investigation of fleet force levels when larger vehicles had a 50 mm longer deformation zone. These cases resulted in similar acceleration levels in the smaller vehicles, but the force levels of small vehicles still needed to be increased above current levels. Work is ongoing to identify guidelines for the force level profiles for more compatible vehicles.

CONCLUSIONS

The work to date in the VC-Compat project has concentrated on four main activities. These are:

- A structural survey.
- Accident and cost benefit analysis.
- Crash testing.
- Mathematical modelling.

The structural survey is complete and a database of a vehicle's main structural members that are involved in frontal impact crashes has been constructed for 55 cars. This database has been used to better understand the results of crash tests and will be used to help define appropriate assessment areas for the Full Width Deformable Barrier (FWDB) and Progressive Deformable Barrier (PDB) tests.

The accident and cost benefit work has identified the target population for improved compatibility for Europe by extrapolating data from Great Britain and Germany. The target population is defined as those casualties that are likely to experience a reduced risk of injury from improved compatibility measures. The number of casualties prevented, i.e. the benefit, will be a subset of the target population. It was estimated that between 14% (3,466) and 31% (7,675) of fatally injured car occupants and between 29% (50,260) and 52% (90,122) of seriously injured car occupants lie within the target population for Europe.

Crash testing work to date has focused on the development and validation of the FWDB and PDB test procedures. Car-to-car testing has been performed which showed that the structural interaction performance of a two-level load path car was better than a one-level load path vehicle. This supports the use of assessment criteria that encourage car design with good vertical load spreading capability. The FWDB and PDB test tools have been shown to be capable of distinguishing the presence of subframe load paths and different bumper crossbeam behaviour. The proposed FWDB and PDB assessment criteria have been calculated and compared for a range of vehicles. At this stage it appears likely that both the FWDB and PDB assessment criteria require further development. However, there is a shortage of car-to-car test validation data. Future work is planned to address these issues.

A Finite Element (FE) model of the FWDB has been developed and used to investigate the sensitivity of the relative homogeneity criteria to alignment of the car with the LCW. The results showed a high sensitivity to vertical alignment for a non-homogeneous, i.e. incompatible, vehicle. To ensure test repeatability for this type of vehicle it has been estimated that vertical alignment tolerances of the order of +/- 10 mm will be required. A vehicle fleet model has been developed using the MADYMO software. This will be used to quantify the benefits of improved compatibility in the vehicle fleet. Studies to investigate the frontal force mismatch in the current fleet indicate that changes to both light and heavy vehicles are needed.

The EEVC WG15 route map requires a test procedure to assess a vehicle's structural interaction potential in the short term. The VC-Compat project will continue to focus on the development of the FWDB and PDB test procedures as both these tests have the potential to achieve this goal.

The VC-Compat Car-to-Car Research Team:
TRL: Mervyn Edwards, Huw Davies
UTAC: Pierre Castaing, Tiphaine Martin, Pascal Delannoy
BASt: Eberhard Faerber, Claus Pastor, Richard Damm
Chalmers: Robert Thomson, Fredrik Jenefeldt
FIAT: Giancarlo Della Valle, Domenico Galeazzi
TNO: Cor van der Zweep, Gijs Kellendonk

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TOWARDS A BENEFICIAL, SCIENTIFICALLY MEANINGFUL, AND APPLICABLE COMPATIBILITY-TESTING

Robert Zobel
Thomas Schwarz
Gareth Thomas
Volkswagen AG
Germany
Paper Number 05-0052

ABSTRACT

Compatibility is an issue that relates to the improvement of vehicle safety. After frontal and side impact self protection, partner protection, a key component of compatibility, represents the next step forward for passive safety improvement. Compatibility is complicated to achieve, because it requires world-wide industry to take steps in a similar direction. A harmonized approach is difficult to achieve because many differences in vehicle makes and models between the various fleets around the world exist. This leads to incompatibilities between vehicles in a global sense: Asian markets have a high market share of very small cars, the American market is characterized by a high proportion of LTVs and SUVs and the European market is somewhere between the American and the Asian markets.

It is obvious that a lot of requirements need to be fulfilled by a compatibility regulation which is; beneficial to the customer, which is scientifically meaningful, refers to front and side-impact and which is applicable for all markets and, last but not least, is considered to be fair by all manufacturers.

ACEA is not in the position to suggest a solution meeting all these requirements. However, some test results and observations which could contribute to a solution are presented in this paper.

The focus of most proposed compatibility procedures is to improve structural interaction in collisions involving passenger cars. A couple of conditions exist that influence the definition of a geometric zone for structural interaction. A zone for structural interaction has to ensure maximal interaction between passenger vehicles with other passengers vehicles, SUVs/LTV's and trucks (to be supported by under-run protection systems) can be achieved. This could represent a first step in increasing compatibility within vehicle fleets. Structural interaction is, in fact, the principle requirement for compatibility before the issue of stiffness can be solved. Keeping this in mind, ACEA drafted a road map chartering the path toward improved compatibility, which is presented in this paper.

INTRODUCTION

Accident Findings

There are two main areas of interest when discussing accidents: Single vehicle accidents and vehicle-to-vehicle accidents. In single vehicle accidents, the object is mainly rigid. All deformation energy has to be provided by the vehicle itself. In car-to-car accidents, both opponents provide deformation energy and the technical challenge is to enhance the interaction of both objects so that all available deformation energy is dissipated in a collision.

There is a clear finding in Europe and in the U.S regarding the distribution of single vehicle accidents and vehicle-to-vehicle accidents. Single vehicle accidents are of very high statistical significance and have to be taken into account when discussing partner protection and compatibility.

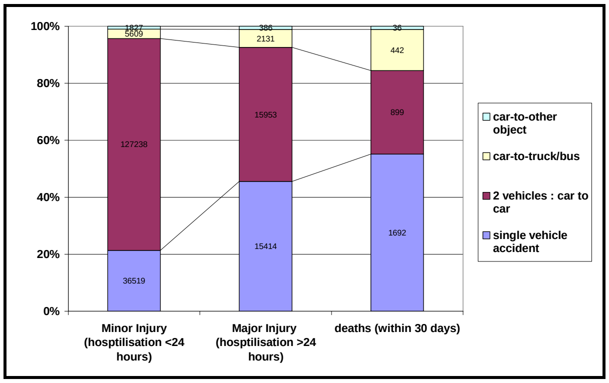


Figure 1: Distribution of car-to-car accidents, car-to-truck accidents and single vehicle accidents in Germany 2003 (StBA).

German data clearly indicates that single vehicle accidents are very relevant when considering fatalities Figure 1.

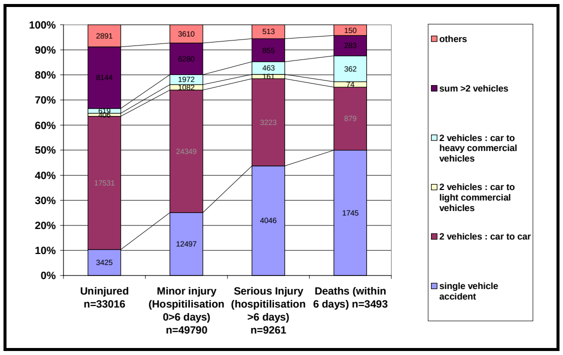


Figure 2: Distribution of car-to-car accidents, car to light and heavy truck accidents and single vehicle accidents in France 2003 (LAB).

The same observation holds true for France, approximately 50% of the fatalities occur in single vehicle accidents Figure 2.

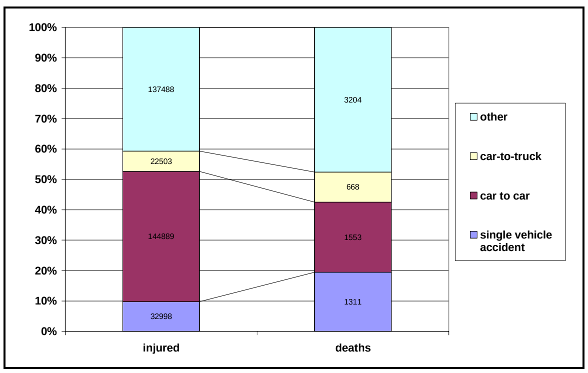


Figure 3: Distribution of car-to-car accidents and single vehicle accidents in Italy 2002 (ISTAT).

The situation is a little different in Italy regarding fatalities in single vehicle accidents and car-to-car accidents. Both accident configurations are of nearly equal relevance. In the Italian statistics, all participants in traffic accidents are included (pedestrians and motorcyclists are included). This explains the high percentage of "others" Figure 3.

When considering occupants that sustain injuries of lower severity only, the opposite observation is true. Car-to-car accidents are of higher statistical relevance than single vehicle accidents when considering less severe injuries. Severe injuries are somewhere in between, close to the distribution of the fatalities. The distribution of collision objects for occupants injured in accidents involving long term consequences can be estimated to more closely reflect the distribution for fatalities than for slight injuries. Unfortunately, the official statistics do not provide this information.

Both sides of car safety (self- and partner-protection) should be taken into account when discussing safety enhancement. European car industry started its own compatibility research with the unanimous understanding that compatibility means an enhancement of overall safety of cars without compromising the existing safety level of cars provided to the cars' own occupants (self protection). The figures above, which reflect the accident environment in most developed countries, prove that a good balance between self and partner protection is a pre-requisite for an enhancement of the protection of passenger vehicle occupants.

Measuring Self Protection

Self protection is generally evaluated in crash tests and the dummy loads measured in the tests often form the basis of the safety evaluation. These parameters describe the risk faced by an occupant during a collision in the configuration tested. In fact, no vehicle occupant will ever be involved in an accident in a configuration identical to the crash-test. What is the real-world safety benefit e.g. of a rigid-barrier impact for an occupant involved in a collision with a tree? Is the amount of deformation energy available for this pole impact the same? Of course and unfortunately, the energy, dissipated in the front-end in a rigid barrier impact is an upper limit for the deformation energy available for an impact with a pole or tree. The tree may strike one longitudinal and miss the other, or the tree may strike the vehicle between the longitudinals. The deformation energy available within the longitudinals would not be available in this case as it is unlikely the cross beam could transmit the loading to both longitudinals.

When a rigid barrier is used, the amount of energy absorbed by the car is easily measured. It is almost equal the kinetic energy of the car before the crash (neglecting rebound). All energy has to be absorbed by the car, because the barrier does not absorb any energy. This was the reason that EES, the Energy Equivalent Speed, was formulated. The EES is the speed a car needs in an impact against a rigid barrier to absorb a certain amount of deformation energy.

D Deformation Energy

m Mass of Car

$$D = \frac{1}{2} * m * EES^2 \qquad (1)$$

$$\Rightarrow EES = \sqrt{\frac{2D}{m}}$$

The EES is a first approximation about the amount of self protection provided by a car. A couple of restrictions which apply to the statement mentioned above must be taken into account. However, it is a basis to ensure that a certain level of self protection is provided.

It was already mentioned that the EES can be easily calculated for a rigid barrier impact. However, barriers with deformable elements are being discussed for compatibility testing that absorb energy as well. The consequences this has for the EES have to be investigated.

Three types of barriers have to be distinguished:

- **Zero Deformation Energy Barrier ZDEB.**

This is, in-fact, a rigid barrier, as used in the U.S.

- **Limited Deformation Energy Barrier LDEB.**

This is a barrier that provides deformation energy, but the car will bottom out the barrier and the barrier behaves like a rigid-barrier at the end of the collision. (ECE R94 in Europe)

- **Unlimited Deformation Energy Barrier UDEB.**

This is a barrier that provides sufficient deformation energy, so that the car will never bottom out the barrier. This barrier never behaves like a rigid barrier.

Each of these barrier types are used or available as research tools. There are well known facts about these barrier types:

- Zero deformation energy barrier energy ZDEB:
  - Induces simultaneous/homogenous deformation-shear loads not activated
  - Cross-beams are not credited
  - Not representative of real-world car-to-car impact
- Limited deformation energy barrier LDEB:
  - Barrier provides shear loading only in the early stages of deformation, until bottoming-out occurs
  - To maximize energy dissipation within the barrier, wide load distribution in vertical direction is beneficial
- Unlimited deformation energy barrier UDEB:
  - Barrier always provides sheer load
  - Car will never bottom out barrier
  - Barrier never behaves like a rigid object
  - Is not representative of impacts with rigid objects

The purpose of this paper is not to discuss all these issue in depth. This list is also not complete. It only shows the main implications for compatibility. The question that has to be answered is; what is the influence of each barrier type on the EES?

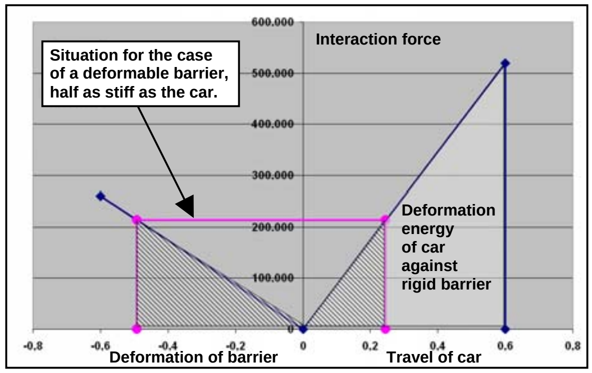


Figure 4: Energy distribution in the front-end of the car and in the barrier when the deformation characteristics of both objects can be described using triangular force-deflection-curves.

Figure 4 outlines the problem. A car, tested against a deformable barrier needs less deformation of its own structure to dissipate it own kinetic energy than a car tested against a rigid barrier. This means that the deformable barrier collision test self protection to a low degree than collision against the rigid barrier. The relationship between barrier stiffness and the self protection level of the car are easily computed using the following formulae.

c_{car} Stiffness of car

$c_{barrier}$ Stiffness of barrier

F Interaction force level

d Deformation travel

$$c_{car} * d_{car} = F = c_{barrier} * d_{barrier}$$

D Deformation energy in case of car - to - barrier impact

$$D = D_{car} + D_{barrier} = \frac{1}{2} * d_{car} * F + \frac{1}{2} * d_{barrier} * F$$

$$D = \frac{1}{2} * \frac{F}{c_{car}} * F + \frac{1}{2} * \frac{F}{c_{barrier}} * F = \frac{1}{2} * F^2 * \left(\frac{1}{c_{car}} + \frac{1}{c_{barrier}} \right)$$

Assuming there is force equilibrium at the interface between the car and barrier (action and reaction), the deformation travel of the car and the barrier is reciprocally proportional to the stiffness of the car and barrier, respectively. This allows the computation of the energy for a triangular force-deflection-curve. From this, the proportion of D_{car} compared to the total energy of the crash is easily computed.

$$D_{car} = \frac{1}{2} * d_{car} * F = \frac{1}{2} * \frac{F}{c_{car}} * F = \frac{1}{2} * \frac{F^2}{c_{car}}$$

$$\frac{D_{car}}{D} = \frac{\frac{1}{2} * \frac{F^2}{c_{car}}}{\frac{1}{2} * F^2 * \left(\frac{1}{c_{car}} + \frac{1}{c_{barrier}} \right)} = \frac{\frac{1}{c_{car}}}{\frac{1}{c_{car}} + \frac{1}{c_{barrier}}} = \frac{1}{1 + \frac{c_{car}}{c_{barrier}}}$$

$$\frac{D_{car}}{D} = 50\% \quad \text{for} \quad c_{car} = c_{barrier}$$

$$\frac{D_{car}}{D} \approx 0\% \quad \text{for} \quad c_{car} \text{ large compared to } c_{barrier}$$

$$\frac{D_{car}}{D} \approx 100\% \quad \text{for} \quad c_{car} \text{ small compared to } c_{barrier}$$

For rigid barriers, c_{car} is negligible and the car has to absorb 100% of the deformation energy. If both car and barrier are similar, then only 50% of the kinetic energy has to be absorbed by the car. For a very deep barrier with unlimited available deformation energy, very stiff cars may deform the deformable element to a very large extent. In this case, little energy would be dissipated through deformation of the vehicle structure. High stiffness is not penalized by this barrier.

This can easily be transformed into the notion of EES. Considering the Barrier Impact Speed BIS, the following computation holds:

$$c_{car} = c_{barrier} \Rightarrow \frac{D_{car}}{D} = 50\% \Rightarrow \frac{EES}{BIS} = 71\%$$

$$\Rightarrow \quad EES = 39{,}6km/h \quad \text{for} \quad BIS = 56km/h$$

$$c_{car} \quad \text{large compared to} \quad c_{barrier} \Rightarrow \frac{D_{car}}{D} \approx 0\% \Rightarrow \frac{EES}{BIS} \approx 0\%$$

$$\Rightarrow \quad EES \approx 0km/h \quad \text{for} \quad BIS = 56km/h$$

$$c_{car} \quad \text{small compared to} \quad c_{barrier} \Rightarrow \frac{D_{car}}{D} \approx 100\% \Rightarrow \frac{EES}{BIS} \approx 100\%$$

$$\Rightarrow \quad EES \approx 56km/h \quad \text{for} \quad BIS = 56km/h$$

So, what remains in terms of self protection, when a barrier impact speed of 56km/h is used?: If both the car and the barrier have of the same stiffness, the EES (desribing the level of self protection) decreases to 40km/h.

Another question, often raised when discussing these different barrier types, is the question of mass influence. LDEBs, like the European R94 barrier, are often blamed for containing a mass dependency. The barrier provides a limited amount of deformation energy. A larger car, which has more kinetic energy at a given barrier impact speed BIS, receives a smaller percentage of its initial kinetic energy through deformation of the barrier than a small car. In absolute terms, both cars can absorb the same amount of energy but this amount represents a higher percentage of the initial kinetic energy of the small car. So, small cars are tested at a lower EES than large cars. **Figure 5** gives the relation.

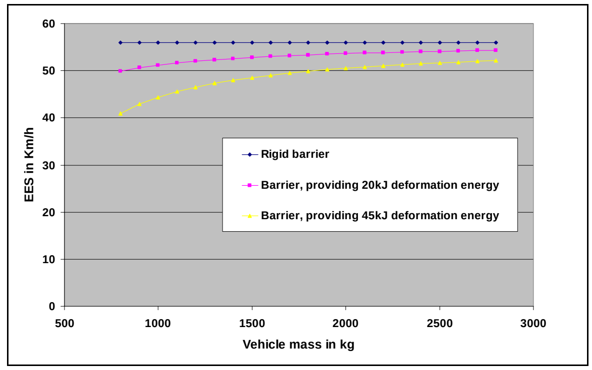


Figure 5: Mass influence of EES in LDEB barriers which provide a limited amount of deformation energy.

In the formula, previously presented, it was clear that the UDEBs (barriers providing an unlimited amount of deformation energy) provide deformation energy to the car depending on the stiffness of car and barrier:

$$\frac{D_{car}}{D} = \frac{1}{1 + \frac{c_{car}}{c_{barrier}}} \Rightarrow \frac{D_{barrier}}{D} = 1 - \frac{1}{1 + \frac{c_{car}}{c_{barrier}}} = \frac{1}{1 + \frac{c_{barrier}}{c_{car}}}$$

This formula clearly depends on stiffness. Unfortunately, there is a relationship between stiffness and mass, because car designers are not free to design cars with unlimited amounts of deformation travel. Therefore current cars have a similar degree of available deformation travel, which is nearly the same for all mass classes. This creates the mass influence for the UDEBs.

$$\frac{1}{2} * m_{car} * BIS^2 = D = \frac{1}{2} * F_{car}^{\max} * d_{car} \quad \text{for triangular force - deflection curves}$$

$$F_{car}^{\max} = \frac{\frac{1}{2} * m_{car} * BIS^2}{\frac{1}{2} * d_{car}} = \frac{m_{car} * BIS^2}{d_{car}} \quad \text{and} \quad c_{car} = \frac{F_{car}^{\max}}{d_{car}} = \frac{m_{car} * BIS^2}{d_{car}^2}$$

m_0 mass of average car simulated by barrier

d_0 deformation travel of average car simulated by barrier

Assumption : Not much difference between cars,
regarding deformation travel : $d_0 = d_{car}$

$$c_{barrier} = \frac{m_0 * BIS^2}{d_0^2} \quad \text{and} \quad \frac{c_{car}}{c_{barrier}} = \frac{m_{car}}{m_0}$$

$$\frac{D_{car}}{D} = \frac{1}{1 + \frac{c_{car}}{c_{barrier}}} = \frac{1}{1 + \frac{m_{car}}{m_0}} < 1 \quad \text{and} \quad \frac{EES}{BIS} = \sqrt{\frac{D_{car}}{D}} = \sqrt{\frac{1}{1 + \frac{m_{car}}{m_0}}}$$

Although there is no theoretical influence of mass, an influence is present driven by the fact that deformation travel of cars is limited. This influence is described in the following figure 6.

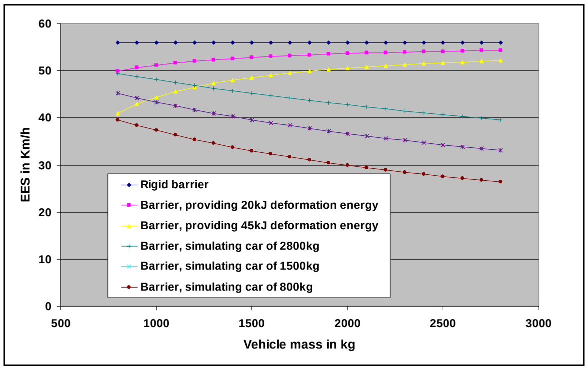


Figure 6: The inter-dependency between mass and EES for cars designed for collisions against LDEB barriers and ZDEB, respectively.

Concluding this section, the following can be stated:

A vehicle with lower available deformation travel has higher front-end forces and will be tested at a lower EES by an UDEB, a barrier providing an unlimited amount of deformation energy. As all of today's cars have nearly the same deformation travel (40cm...70cm), larger cars are stiffer than smaller cars and therefore will be tested at a lower EES level. This means that they will provide a lower self protection level.

Avoidance of bottoming out costs a high price leading to a reduction in self protection in single vehicle accidents <u>and</u> vehicle-to-vehicle collisions.

Referring to the bulkhead principle, compartment collapse can be avoided up to the sum of the EES of both vehicles in fixed barrier collisions. This is achievable because there is sufficient deformation energy available within the front-ends of both vehicles for this particular crash configuration.

If the EES of one of the vehicles is reduced, the maximum closing velocity, up to which achieving compatibility can be considered realistic, would be reduced as well [1].

Steps toward Partner Protection -
The Stiffness of the Crossbeam

ACEA conducted no own research on a special barrier, nor does ACEA wish to establish its own one. The main focus of ACEA is to discuss and evaluate the existing ideas of compatibility barriers. The member companies of ACEA do not have a common position on one barrier type or assessment procedure. The position of ACEA is that the current knowledge is not sufficient to make this decision. The calculation given in the previous paragraph is an example of such research. It is pure physics, so no decision was taken within ACEA about this issue. The common position of all partners is that self protection must not be compromised. The path to achieve this goal is still under discussion.

Besides the question, which barrier is the most appropriate one resulting in a maximum increase in safety, there is also the question of side effects that has to be studied carefully. So ACEA performed two test series.

A Rover 75, which was already tested in the previous EUCAR-project on compatibility, was tested by ACEA with three different crossbeams: A stiffened crossbeam, a serial crossbeam and a weakened crossbeam (Figure 7,Figure 10 and Figure 13). The idea was that homogeneity of front structures is beneficial. A crossbeam improves the distribution of forces exhibited by the front-end of a car and therefore the homogeneity, at least on the level of the longitudinals. This offered the opportunity to check how test procedures under consideration evaluated this change in front-end design.

Two barriers were used: The barrier designed by TRL with two deformable honeycomb layers of 150mm each and 125*125 mm² load cells, the FWB. The barrier, designed by French researchers, using a deformable layer with increasing stiffness, the PDB.

The results to these tests were presented to EEVC and IHRA to make them available to the scientific public. A brief overview of the results is given.

Figure 7: Rover 75 with a strengthened crossbeam.

After the crash with the full-width barrier, the crossbeam was deformed and creased in the middle Figure 8.

Figure 8: Rover 75 with a strengthened crossbeam after crash with FWB.

A surprising result was that the strengthened crossbeam was not stiff compared to the barrier. This indicates that our opinion about "stiff" crossbeams has to be revised with regard to load distribution.

Figure 9: Rover 75 with a strengthened crossbeam after crash with PDB.

The same figures are provided for the serial and weakened crossbeams:

Figure 10: Rover 75 with a serial crossbeam.

Figure 11: Rover 75 with a serial crossbeam after test with FWB.

Figure 12: Rover 75 with a serial crossbeam after test with PDB.

Figure 13: Rover 75 with a weakened crossbeam.

Figure 14: Rover 75 with a weakened crossbeam after crash with FWB.

It is not possible to provide the many different observations that could be derived from this test series. Only the main findings are reported:

Both barriers, when visually inspected, showed an imprint that reflected the different stiffness of the crossbeams.

When observing the deformation of the FWB, the visual inspection showed clearly the deeper imprint in the barrier by the stiffer crossbeam. After scanning the imprint, results showed that the strengthened crossbeam deformed 43.5% of the assessment area more than 150mm, the serial crossbeam only 28.2% and the weakened layer only 22.8%. (the assessment area was located between 330mm and 580mm of ground clearance).

Figure 15. Rover 75 with a weakened crossbeam after a test with the PDB.

The PDB distinguished the three crossbeams, when the deformation of the longitudinals was considered. The strengthened crossbeam induced a longitudinal deformation of 427mm, the serial crossbeam 354mm and the weakened 178mm. This was an evident result, because the stiffer the crossbeam, the more load the crossbeam can distribute to the longitudinals and the more the longitudinals will deform.

Although this indicated that the barriers behaved in an manner expected, all other assessment procedures under consideration (PDB assessment and TRL homogeneity assessment) failed [2,3].

This raised the question of the validity of force and/or deformation measurement. This was the reason, to conduct a second test series, discussing the reproducibility of the data. The question was whether the assessment procedures failed, because they were wrong or in a certain way misleading or because the data were too biased due to measurement problems, so that a test procedure is not able to derive a valid result.

Steps toward Partner Protection

The Reproducibility of Test Results in the FWB and PDB configuration

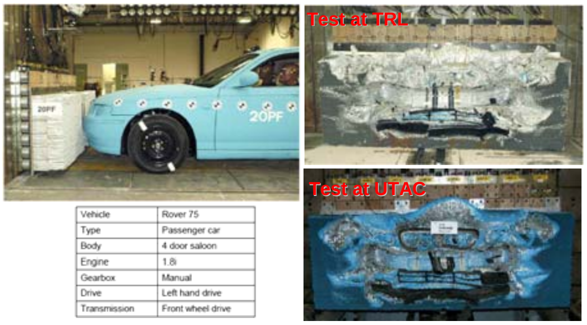
<u>Full Width Test FWB</u>

A full width test was already conducted at TRL in the United Kingdom. So another test was conducted at UTAC in France. The test was in fact a reproducibility test, examining the test procedure itself, the assessment procedure and the definition of the test procedure, whether another test institute is able to regain the results.

The test conditions were:

- Overlap 100%
- Speed 56km/h
- Load Cell Wall 16x8 Matrix @ 125mm2
- Deformable Face of Aluminum Honeycomb
- Barrier Faces
  150 mm @ 0.34 MPa
  150 mm @ 1.71 MPa
- Ground Clearance 50mm TRL and 80mm UTAC

The different ground clearance was consequence of the fact that the test procedure had changed during the performance of the two tests. Another difference between the two tests was the different ride height of the two cars. This resulted in a difference in impact point with respect to the grid of load cell attached to the rigid wall. The difference in impact point, measured with respect the lower edge of the load cell grid, was 46.5mm. The difference in impact points with respect to the ground was 16.5mm. In the TRL test, the car impacts the wall 46.5mm higher within the load cell grid than in the UTAC test. In other words, the assessment area of the TRL test was 46mm lower than in the UTAC test. The load cells were square with the dimension of each side equal to 125mm. 46.5mm reflects around a 30% overlap of the load cell in the vertical direction. This may have had implications for the force measurement. The implications for the deformation measurement can be considered to be negligible.



Vehicle	Rover 75
Type	Passenger car
Body	4 door saloon
Engine	1.8i
Gearbox	Manual
Drive	Left hand drive
Transmission	Front wheel drive

Figure 16: Reproducibility test - Rover 75 against a full width barrier.

Visual inspection of both barriers shows similar deformation behavior. Although there were differences in ride height, the imprints of the sub-frame, longitudinal and crossbeam were seen in both barriers. The deformation based results appear reliable, Figure 16. The force based results may be influenced by the difference in vehicle ride-height and barrier deformation.

The same holds true for the cars, Figure 17 and Figure 18. Visual inspection of both cars reveals a similar structural behavior. In both cars, similar welding spots of the Rover75 longitudinal failed.

Figure 17: Deformation of the Rover 75, tested in full width test at TRL.

Figure 18: Deformation of the Rover 75, tested in full width test at UTAC.

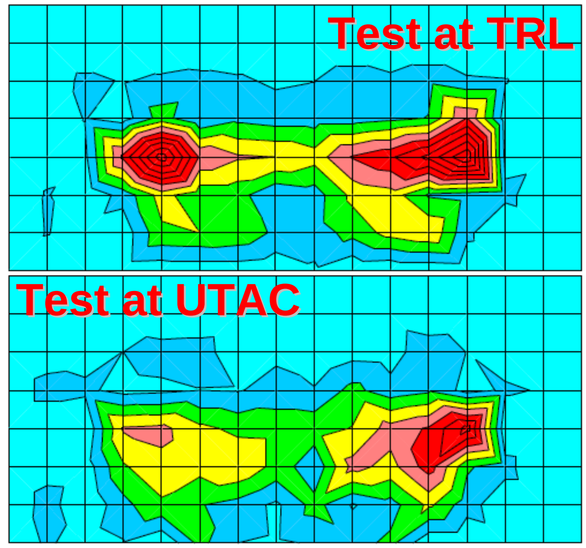


Figure 19: Force contour plots of the Rover 75, tested in full width test.

The imprint in the layer looks similar, but the force contour plots show differences. Figure 19 shows that longitudinal in the UTAC-test was deformed to a lesser degree than in the TRL-test, explaining the higher forces in TRL-test. But this is not reflected by compartment acceleration. The deceleration curves are similar, besides a difference in the peak acceleration over a time interval of 10 ms duration Figure 20.

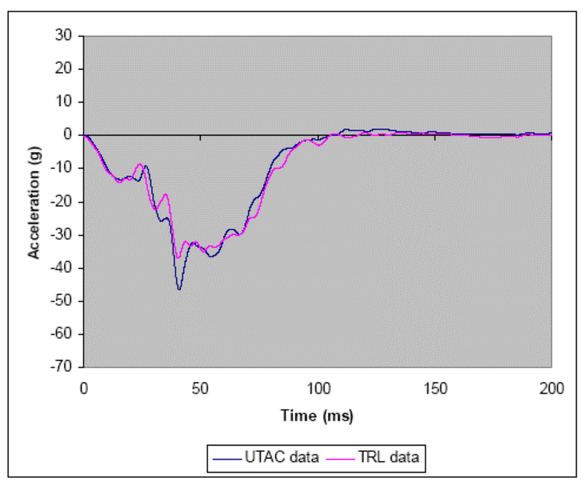


Figure 20: Acceleration plots of the Rover 75, tested in full width test.

Due to the differences seen in the force contour plot, a reaction of the homogeneity criterion would be expected. But the homogeneity criterion does not react significantly. The relative homogeneity is similar for both tests, although the TRL test shows a slightly better homogeneity Figure 21. The same holds true for the adjusted Average Height of Force AHOF. It was adjusted to the ride height differences mentioned above. The values for the AHOF were 411mm and 420mm for the test at UTAC and TRL, respectively.

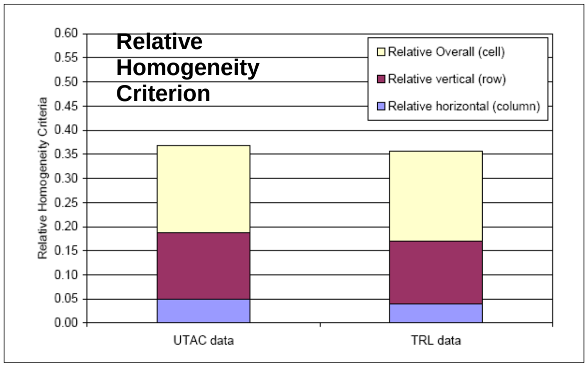


Figure 21: The relative homogeneity of the Rover 75, tested in full width test.[2]

There is an instability of the barrier deformation as well. The deformation of the barrier (vehicle imprint) is described by a cumulative curve in Figure 22. This describes the percentage of the assessment area which was deformed in each cumulative depth increment, from the wall to the front-face of the barrier (assessment area 1600mm wide with a lower limit at 330mm and an upper limit at 580mm). At 150mm (the interface plane between the two layers) this curve describes the percentage of the assessment area that has a completely deformed second layer. The assessment area corresponds to row 3 and 4 of the load cell wall (for a load cell wall ground clearance of 80mm) and the width covers all load cells hit by the longitudinals and in those in between. For force measurement, this adjustment was not possible.

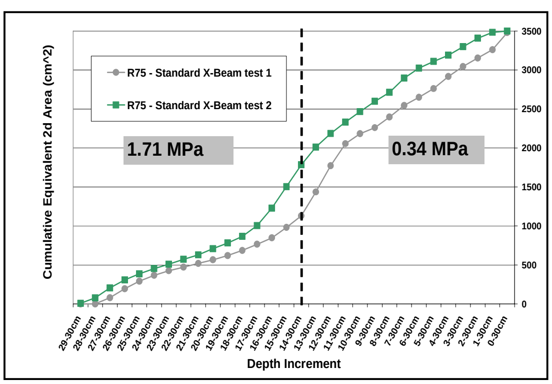


Figure 22: The deformation of the Rover 75, for tests carried out at UTAC and TRL, respectively.

Figure 22 shows a significant difference between the two cars, especially in the range of 20mm to 200mm. This has to be examined further on, because there is an expectation that deformation is a stable value. This test series indicates that this is not always the case.

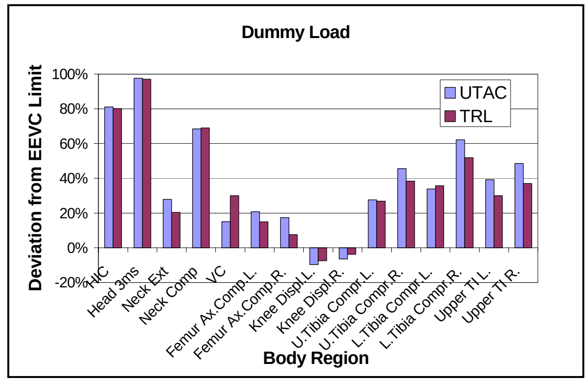


Figure 23: The dummy load of the driver of the Rover 75, tested in full width test.

Dummy loads were not the main focus of this test series but they were measured and documented in Figure 23and Figure 24. Roughly speaking, HIC and neck criteria are similar and the other body regions show differences, which are substantial in some cases.

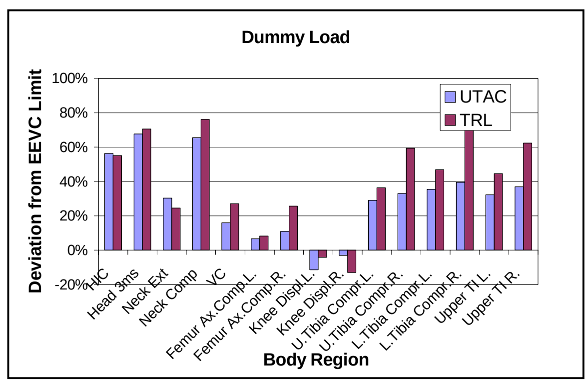


Figure 24: The dummy load of the passenger of the Rover 75, tested in full width test.

Progressive Deformable Barrier PDB

A Rover 75 test with PDB, conducted by ACEA at UTAC, already existed. So a second test was conducted at TRL in accordance to the PDB-test procedure.

UTAC test

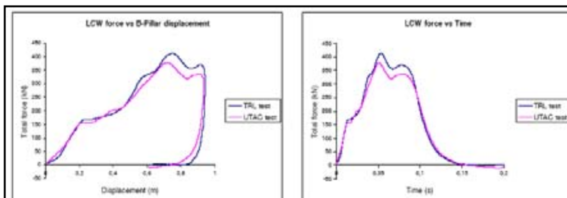
TRL test

Figure 25: The deformation of the Rover 75, tested in the PDB configuration.

There are clear differences in the deformation of the car. These are partially due to the car itself. The welding spots in the two cars, which were both manufactured in the same year, were different. So for all FWB-tested cars and the UTAC-PDB tested car, some of the welding spots failed.

Figure 26: The longitudinal of the Rover 75, tested with PDB.

The upper picture shows the behavior of the car tested at UTAC. This corresponds to the behavior of all longitudinals in FWB-testing. The lower picture shows the behavior of the car tested at TRL. The position of the welding spots was different for this car.



ROVER 75	Ec	Calculated energy	Maximum force
UTAC	220 kJ	211 kJ	378 kN
TRL	223 kJ	225 kJ	413 kN

Figure 27: The total force of the Rover 75, tested by PDB.

The total force plots, Figure 27, show slight differences which reflect the fact that the longitudinal behaved differently in both tests. The calculated energy was calculated based on the volume of the barrier deformation. These differences indicate that there are slight differences in deformation as well. Unfortunately, for the PDB, a curve comparable to Figure 22 is not available. However, there is a contour plot of the deformation available, Figure 28.

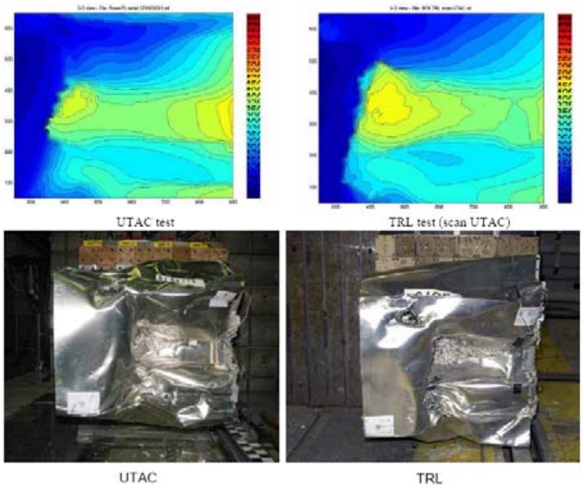


Figure 28. The deformation of the PDB against Rover 75.

The deformation plots reflect the different deformation modes of the longitudinals as shown in Figure 26. A higher degree of deformation of the longitudinal member means less penetration into the barrier which results in more being applied to the right edge of the PDB, which is loaded during the rotational phase of the car.

ROVER 75	ADOD (X)	AHOD (Z)	Volume	Energy
UTAC test	238 mm	467 mm	146 dm³	60,5 kJ
TRL test (scan UTAC)	236 mm	470 mm	138 dm³	56,5 kJ
Variation	0,8 %	0,6 %	5,4 %	6,6 %

ROVER 75	PPAD
UTAC test	5,5
TRL test	5,7
Variation	3,5 %

Figure 29. Results to different assessment metrics, derived from the PDB-test against Rover 75.

Although the imprint looks different, the assessment does not react significantly.

The TRL test was scanned by TRL and by UTAC. The scans were similar, so that scanning can be understood as a stable measurement at a given barrier deformation.

When observing both vehicles (post-crash), the behavior of the longitudinals is clearly reflected by the deformation of the cars, Figure 30.

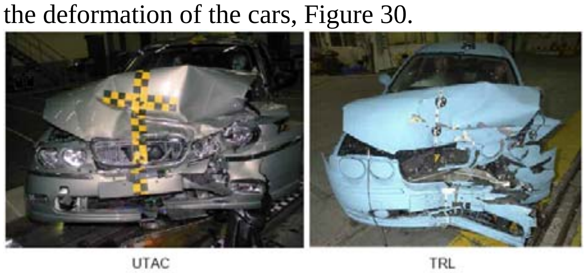


Figure 30. Post crash photographs of Rover 75's crashed at UTAC and TRL in the PDB configuration.

Performance parameter		Driver UTAC	Driver TRL	Driver Diff*(%)	Passenger UTAC	Passenger TRL	Passenger Diff*(%)	EEVC limits
Head	HIC	480	680	+20.0	364	469	+10.5	<1000
	3ms exceedence (g)	54.2	59.9	+7.1	43.7	56.3	+15.6	<80
Neck	Extension –Myoc. (Nm)	29.6	12.0	-30.9	34.4	11.7	-39.9	<57
Chest	Compression (mm)	28.1	38.6	+21.0	26.3	30.7	+8.8	<50
	Viscous criterion (m/s)	0.09	0.19	+10.0	0.11	0.15	+4.0	<1
Knee	Displacement left (mm)	-0.13	-0.63	+3.3	-0.36	-2.72	+15.8	<15
	Displacement right (mm)	-0.79	-0.71	-0.5	-0.63	-0.29	-2.3	<15
Upper tibia	Compression left (kN)	1.38	1.81	+5.4	1.61	1.63	+0.3	<8
	Compression right (kN)	1.32	1.61	+3.6	1.77	1.90	+1.6	<8
Lower tibia	Compression left (kN)	1.48	2.08	+7.5	2.04	2.18	+1.8	<8
	Compression right (kN)	1.61	2.18	+7.1	2.33	2.54	+2.6	<8
Tibia Index	Upper left	0.28	0.31	+2.3	0.31	0.30	-0.8	<1.3
	Upper right	0.29	0.37	+6.2	0.33	0.35	+1.5	<1.3
	Lower left	0.31	0.45	+10.8	0.15	0.19	+3.1	<1.3
	Lower right	0.31	0.24	-5.4	0.13	0.19	+4.6	<1.3

*Difference TRL compared to UTAC and expressed as a percentage of the EEVC limit

Figure 31. The dummy loads measured in the PDB-tests involving the Rover 75.

There are large differences noted for the head, neck and chest injury criteria for the two tests, with worst injury criteria differing by 30.9% and 39.9%, for the driver and passenger respectively. However, in all cases the test measurements did not exceed the EEVC limits.

These repeatability and reproducibility tests showed a couple of interesting results that were not obvious in the beginning. Together with the tests carried out with the Rover 75 with different crossbeams, they raised a lot of questions with regard to an assessment procedure to adequately predict the structural interaction potential of passenger cars.

The Roadmap

Together with these technical problems, there are a couple of problems that are related to the different traffic situation in the U.S., in Europe, in Asia and in the developing countries. The interests of car manufacturers diverge, depending on their model-mix. However, since more and more manufacturers tend to sell the most models in most world-markets, these differences diminish. Last but not least, there is also a concern about impacts with trucks. A car structure should be able to interact with a truck under-run protection system. These are the conflicts of goals that have to be solved by a compatibility test procedure.

Car mass and the type of car (e.g. passenger car, MPV, Mini-Bus, SUV etc) reflect customer demand. It is the unanimous position of automotive industry that compatibility requirements should be made in such a way that customer demand can be fulfilled in the future as well. A restriction of mass, for example, is unacceptable and makes no sense as long as trucks are still on the road. This statement is also true considering the structural design of a car. Requirements should address the vehicle performance and not restrict design possibilities.

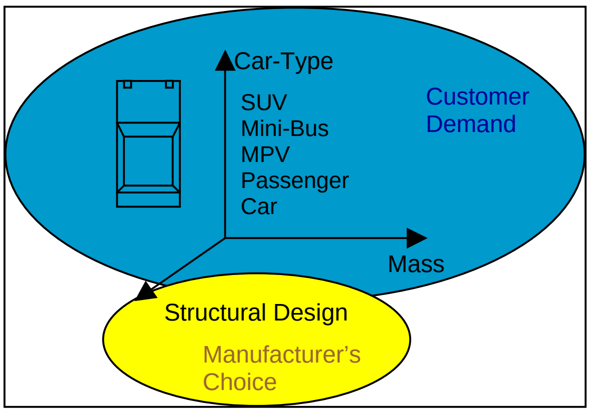


Figure 32: The dimensions of the challenge of compatibility.

Together with the dimensions of the car under consideration, the characteristics of all potential impact objects have to be taken into account as well. .

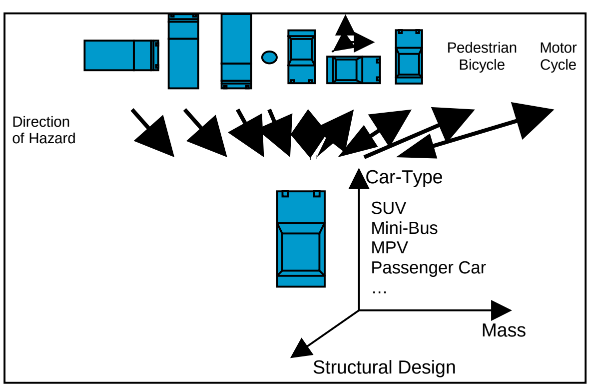


Figure 33: The opponents to be taken into account, when dealing with the challenge of compatibility.

Figure 33 shows the complexity of the challenge to improve compatibility. The idea is not to request a solution to all open questions in one big step. However, it is a reminder, not to worsen the situation in one of these configurations, when improving the situation in another configuration.

When looking at the players (or stakeholders), things become even more complicated, Figure 34. There is a lot of world-wide expectation with regard to compatibility with many parties contributing to compatibility research and decision making. This contribution has a multi-facetted political back-ground,

Figure **35**.

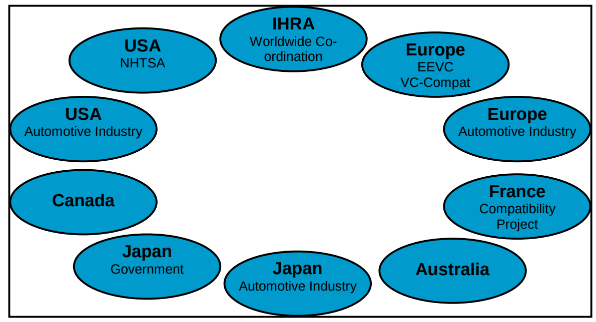


Figure 34: The players.

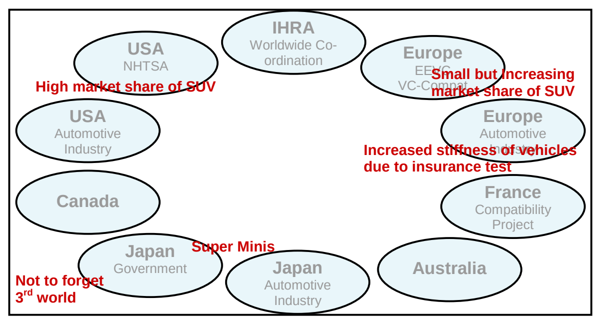


Figure 35: The political back-ground and the restrictions for the players.

In addition to the differences within the current fleets in different regions of the world, there is also different experience in crash testing and different research emphasis, Figure 36.

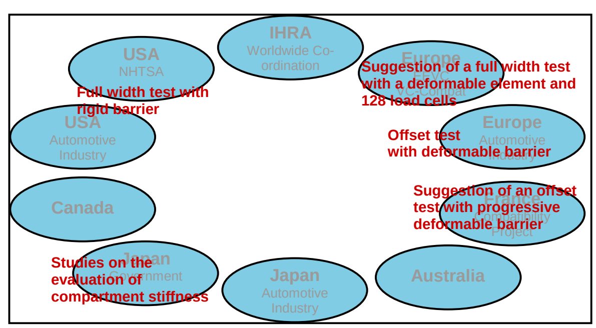


Figure 36: The current situation of convergence between the players.

Taking all of these different aspects into account, ACEA tried to find a step wise approach for compatibility. These are issues which are very difficult to achieve without compromising other goals, such as management of front end forces within the fleet. It is evident that this will never be solved completely, because force requirements between a car of 2000kg and above are definitely different to the force requirements of a car of 800kg. The details are discussed in former ESV papers by the authors. An agreement was made within the automotive industry at the very beginning, that improving structural interaction is the most appropriate first step to improve compatibility. It seems to be possible to achieve this goal without compromising other goals. The goal of structural interaction is in line with the ideas in the U.S.A.

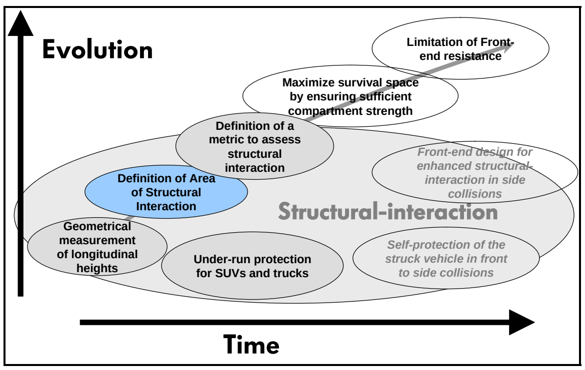


Figure 37: The Road Map.

CONCLUSIONS

- Single vehicle accidents remain a highly relevant collision mode which should not be neglected.
- Self protection should not be compromised by compatibility requirements.
- Tests with deformable barriers have to ensure that the self protection level of the vehicles tested is not reduced. For any mass class, for large and small cars.
- Mass dependent tests should be avoided.
- Tests should be able to detect stable crossbeams as a contribution to homogeneity.
- Current assessment procedures are not able to detect stable crossbeams.
- Assessment procedures have to be studied carefully, how they drive the development of the fleet.
- Reproducibility tests showed that there are still deficits as far as force measurement and deformation measurement is concerned. Further research is required in this area.
- The ACEA reproducibility test series is a worst case scenario. Repeatability tests with absolutely identical case vehicles at the same test institute should follow.
- Customer demand and, as far as possible, manufacturers choice regarding design should not be inhibited by compatibility requirements. Requirements should describe effects not prescribe design. Governmental requirements must be performance and not design-based. To encourage and not stifle innovation, government standards must regulate vehicle performance, but not vehicle design measures.
- Compatibility requirements should be introduced stepwise and in a world wide harmonized manner, because only a harmonized approach is able to result in compatibility fleet across the various world markets.

ACKNOWLEDGEMENTS

This paper is based on scientific research conducted within the ACEA, Sub-group Compatibility (SGC). The first co-author chairs the ACEA SGC and has attempted to summarize the results of numerous discussions that have occurred within the group. The authors wish to express their appreciation to the members for their personal contributions. Virtually all of the member companies believe that it is premature to formulate final conclusions on this complex subject.

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COMPARATIVE EVALUATION OF FRONTAL OFFSET TESTS TO CONTROL SELF AND PARTNER PROTECTION

Pascal Delannoy
Teuchos, Snecma Group - UTAC Passive Safety Department
Tiphaine Martin
UTAC SAS – Passive Safety Department
Pierre Castaing
UTAC SAS - Passive Safety Department

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ABSTRACT

The present demand on self protection and insurance test is increasing the local strength and global force deformation of all cars. Unfortunately, the ratio is not the same, due to the different masses: The design of a large car makes it stiffer than a small one in order to compensate the mass. Furthermore, the current frontal offset test is more severe for heavy vehicles because of the specific barrier used. Due to this self protection trend, compatibility requirements are more and more difficult to achieve.

Moreover, it is yet required to improve light cars compartment's strength without increasing heavy cars' one and to limit vehicle front units' aggressiveness. In other words, it is necessary to assess the possibility to check and improve partner protection with regards to self-protection. To achieve this new requirement, an amendment of ECE R94 test procedure, based on PDB barrier, was proposed in order to check both parts of compatibility (structural interactions -partner- and compartment strength -self-), and is still being studied.

To validate and compare this approach with other offset procedures, many tests have been performed with different cars from European market (light and heavy, old and new generation, left and right hand drive) in different test configurations (current R94 at 56 km/h, possible future R94 at 60 km/h suggested by EEVC WG16 and PDB protocol at 60 km/h).

Based on the tests results, this paper describes in details:
- the comparison of different offset barrier tests
- the validation of PDB test protocol aiming to check self and partner protection
- the possibility to generate constant severity for all cars (same EES)
- the possibility to change the current frontal barrier
- the possibility to assess partner protection and self protection.

INTRODUCTION

Current ODB barrier was developed fifteen years ago and adapted to car designs (geometry and force deformation) from 90's. Since then, introduction of regulation, ratings, insurance test and recently pedestrian have modified a lot car front design in terms of stiffness and geometry to achieve that requirements. The current barrier is becoming more and more obsolete regarding to new generations of vehicles.

With self protection offset test regulations and ratings, all cars offer equivalent behaviour against a fixed obstacle. These tests lead to stiffer front end and higher compartment strength. Solutions have been optimized against a rigid wall or soft obstacle but not in car to car configuration.

A new procedure must not compromise and decrease current self protection level. That is why the proposed procedure in this comparison checks compartment strength and structural interaction on the same time, without introducing additional tests as far as the compatibility demand depends on the vehicle size: Heavy vehicles need a better partner protection (structural interaction), and light vehicles need a better self protection (compartment strength) ***(figure 1)***.

This paper deals with the development of a more comprehensive approach after having studied it different offset tests, aims to propose a test procedure and methodology as good as possible for a regulation approach in several steps towards the improvement of compatibility.

There are no effective proposed improvements unless they are applied by all manufacturers and for all passenger cars. The only way to reach that target is to define and then apply a new regulation.

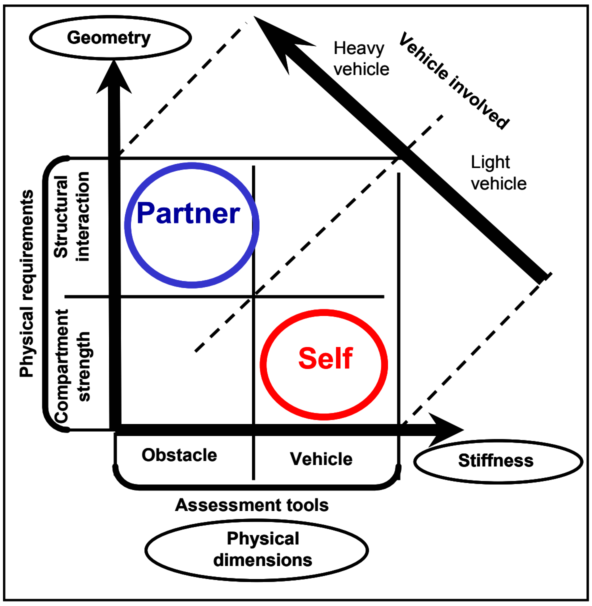


Figure 1: Compatibility summary

FRONTAL TEST PROCEDURE

Three main offset test procedure have been investigated. The current ECE R94, the EEVC WG 16 proposal for assessing self protection and the PDB protocol that takes into account three new parameters to be in line with compatibility requirements:

- partner protection without decreasing self protection against rigid obstacle,
- different vehicle mass range,
- compatibility requirements (self and partner)

Current test procedure

This procedure is fully known all around the world, and most of countries apply this test procedure as a regulation and / or a rating.

Regulation ECE R94:

- Test Speed: 56 km/h
- Overlap: 40 %
- Barrier: current ODB

Figure 2: ECE R94 test configuration (called R94)

EEVC WG16 test procedure proposal

This procedure has been proposed by WG16 to improve self protection against rigid obstacle but could be dangerous for compatibility in terms of self and partner protection.

Derivate from ECE 94:

- **Test Speed: 60 km/h**
- Overlap: 40 %
- Barrier: current ODB

Figure 3: EEVC WG16 test configuration (called R94-60)

PDB test procedure – French proposal

Details of the procedure are fully explained in document "PDB Test Procedure V2-2" published in the EEVC WG15 web site. Test configuration is not so far from current regulation but some essential changes must be included (especially the barrier).

Derivate from PDB test:

- **Test speed: 60 km/h**
- **Overlap: 50 %**
- **Barrier: PDB**

Figure 4: PDB test configuration (called PDB 60)

Compatibility is a mix between self protection and partner protection and can not be separate for investigation because both act simultaneously. Compartment strength is an answer for the first one, homogeneous front end is an answer for the second to improve structural interaction.

<u>Why is a new barrier necessary?</u>

Instability

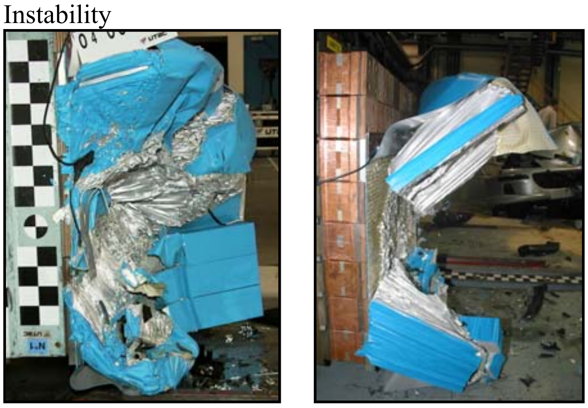


Figure 5: Current ODB barrier instability tested with the same car. Test is not reproducible.

The current barrier was designed many years ago for the previous vehicles generation, weaker than the new one. Since this time, vehicles were reinforced and became stiffer. The stiffer front end leads to unstable behavior of the barrier that creates serious problems in the design of vehicles. Sometimes barrier absorbs energy, sometimes not.

Bottoming out

Each new generation of vehicles bottoms out the barrier (***Figure 6***) that leads same amount of energy absorbed by the barrier.

Figure 6: ODB barrier bottoming out: same amount of energy, structures collapse against rigid wall

The energy absorbed by the barrier does not depend on the vehicle mass. Severity for the vehicle structure rises up with the mass. ***Figure 7*** clearly shows this unequal energy distribution. The fraction of energy absorbed in the barrier is roughly the same regardless of the car mass resulting in a higher fraction of energy to be absorbed by the large vehicle than by the small one. For a light car, energy in the barrier represents 40% of the total kinetic energy but only 10% for a heavy one.

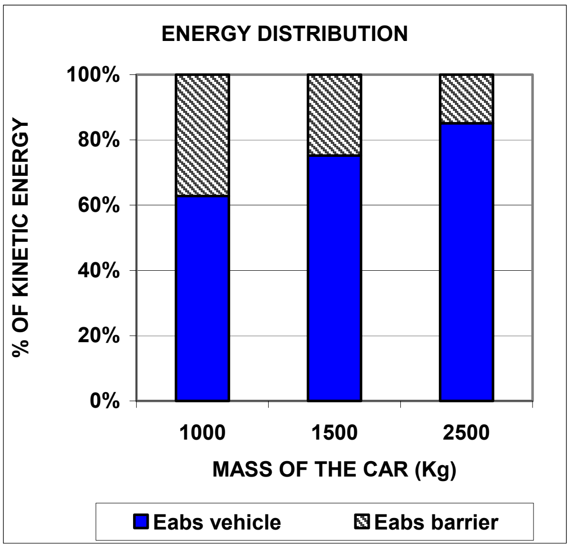


Figure 7: Severity situation with current barrier, percentages of kinetic energy absorbed.

So in order to reach the same level of self-protection, design against deformable barrier with bottoming out results directly in even stiffer heavy cars because this test is more severe than for small ones ***(Figure 8)***.The result is that heavy cars cannot be made compatible, in term of stiffness, with small ones

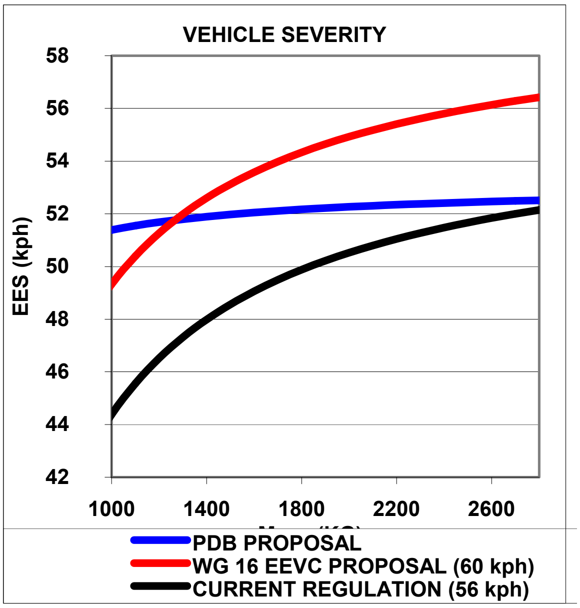


Figure 8: Theoretical Test severity depends on the vehicle mass. Need to harmonize this phenomenon.

Current ODB barrier is not yet adapted to the new generation of cars. It is urgent to harmonize severity for vehicle range mass to reach self protection compatibility requirements and avoid inhomogeneous fleet.

Barrier used

Following test procedures, the PDB barrier was introduced in the comparison. Its high force level and high energy absorption capacity is supposed to resolve the question of bottoming out ***(Figure 9)***.

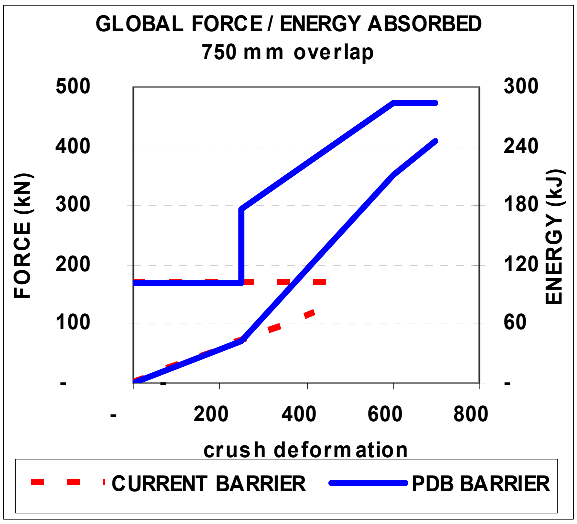


Figure 9: Force and energy capacity comparison for a same overlap

Current ODB barrier

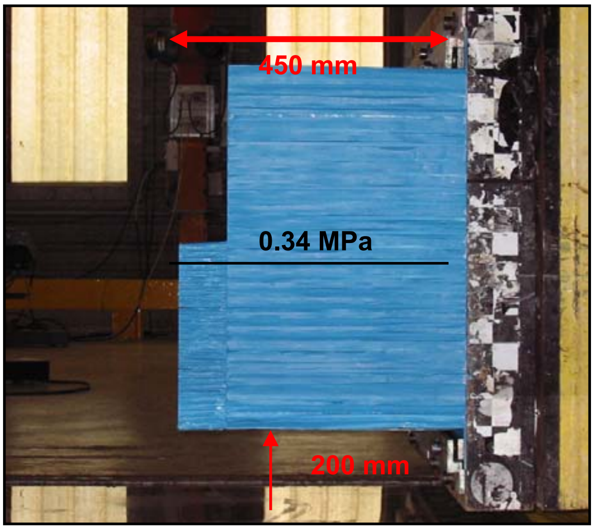


Figure 10: Current ODB barrier - Side view, dimension, position and stiffness.

PDB barrier

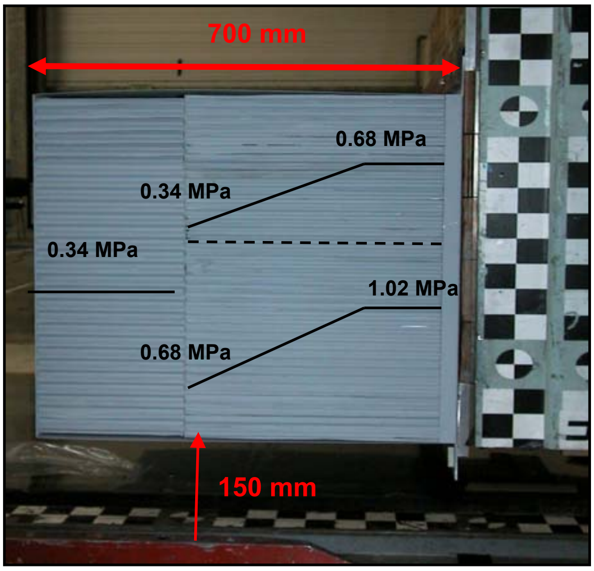


Figure 11: PDB Side view. Dimensions, position and stiffness.

PDB is now well known ***(Figure 11)***. It is a progressive increase in stiffness in the depth, and two height dependant stiffnesses, which contribute to its name: PDB as Progressive Deformable Barrier. Furthermore car force distribution in height should be represented; the lower front load path is usually stronger than the upper one. Its dimensions and stiffness make the bottoming-out phenomenon very unlikely because force and energy capacity are equal to four time the current barrier.

Why a new test speed is needed?

To answer the question of improving compartment strength of the light car, it was necessary to increase the test speed to reach compartment deformation. 60 km/h seams reasonable. Furthermore, this test speed was proposed by EEVC - WG16. However, this increasing speed must be accompanied by a barrier change to reach compatibility requirements to avoid stiffer and stiffer heavy vehicle compartment.

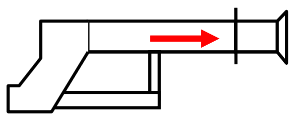
Why a new overlap is needed?

Checking half of the front end is needed for partner protection assessment in the future. Secondly, overlap is closer to real world accident data and car to car test configuration. Finally, combined with stiffer barrier it generates higher acceleration pulse that we will develop in a next chapter.

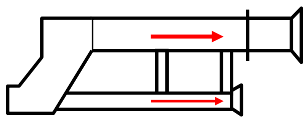
Vehicle type investigated

To demonstrate previous approach, 16 tests were performed with different cars, test configurations and driving position.
Car is tested in regulation approach that means in the worst case: heaviest mass, all options and largest engine. Four cars from French manufacturers have been selected:

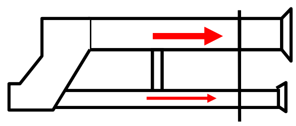
Super Mini Car 1
SMC1 -1151 Kg
New generation- with stiff front single load path and high compartment strength.



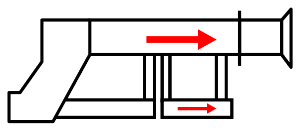
Super Mini Car 2
SMC2 -1130 Kg-
Old generation- with weak front double load paths and weak compartment strength



Family Car 1
FC1-1747Kg-
Last generation- with stiff front double load paths with advanced lower load paths and high compartment strength



Family Car 2
FC2-1677 Kg-
New generation- with stiff single load path with added lower load path and high compartment strength.



Test configurations investigated

Three test configurations have been investigated explained before:

- ECE R94 with current ODB barrier
- Current ODB barrier at 60 km/h
- PDB barrier protocol at 60 km/h

Each vehicle was tested in Left Hand Drive and Right Hand Drive.

TEST RESULTS

Test severity

One of the most important in this study was to check the test severity for each vehicle in terms of energy absorption. ***Figure 12*** represents the amount of energy absorbed by the current ODB barrier and the PDB. The higher absorption potential of the PDB is clearly shown.

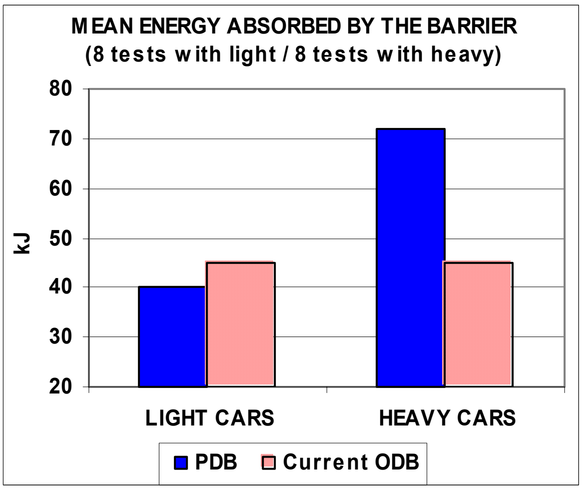


Figure 12: Energy absorbed by the barrier

This leads in a non constant energy absorbed by the vehicle depending on the force deformation.

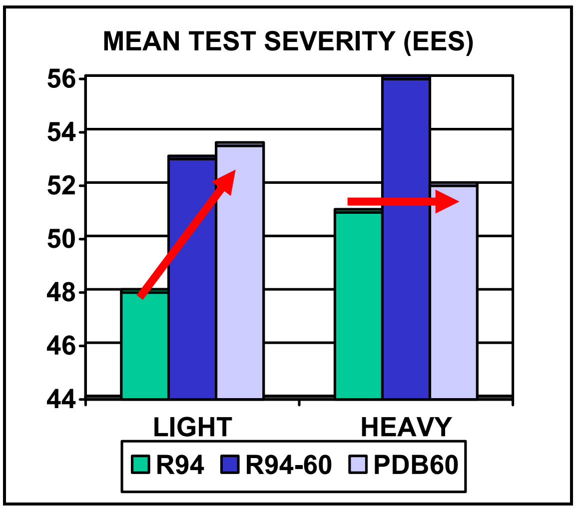


Figure 13: Mean test severity in terms of EES

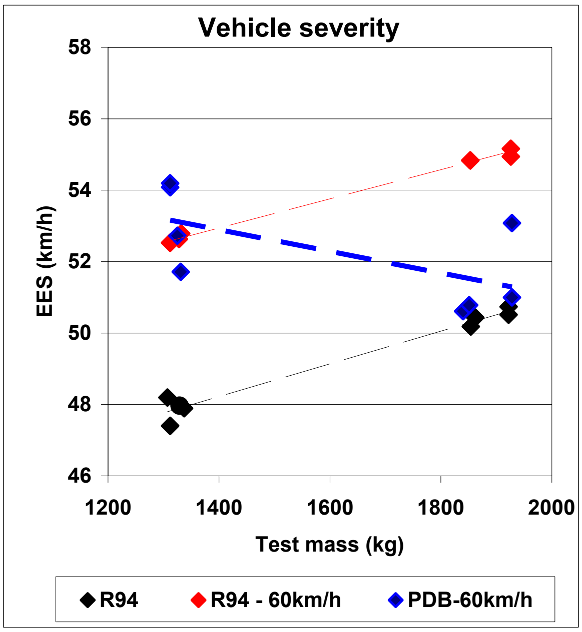


Figure 14: Test severity observed vs Mass

Test confirmed theoretical assumptions. When considering the PDB barrier test, severity in terms of energy absorbed for light cars increased and became close to EEVC WG 16 proposal ***(Figure 13 / 14)***. On the opposite, severity for heavy vehicles stays remained close to current R94 without being below. Current self protection severity is not compromised and light vehicle compartment can be investigated.

Self protection analysis

Car design for frontal crash must limit passenger compartment intrusion and generate acceptable deceleration from the occupant point of view.
Higher acceleration pulse combine with higher intrusion level allows getting closer to real life accident where both parameters are responsible for fatal injuries and injured.

Passenger compartment intrusion

Car to car tests conducted in the past confirm that the front-end stiffness and compartment strength have an influence on compatibility.
Compartment intrusion was shown as the most important parameters in car to car head on collision, so this parameter must be put under control. This parameter is directly linked to the force generated by the compartment.
Compartment intrusions ***(figure 15)*** are going in the same way than EES severity. Light vehicles suffer more in PDB test configuration, especially for the old generation. Severity for heavy vehicles stays constant. Compartment strength principle is validated. Light cars are overloaded without punishing heavy ones.

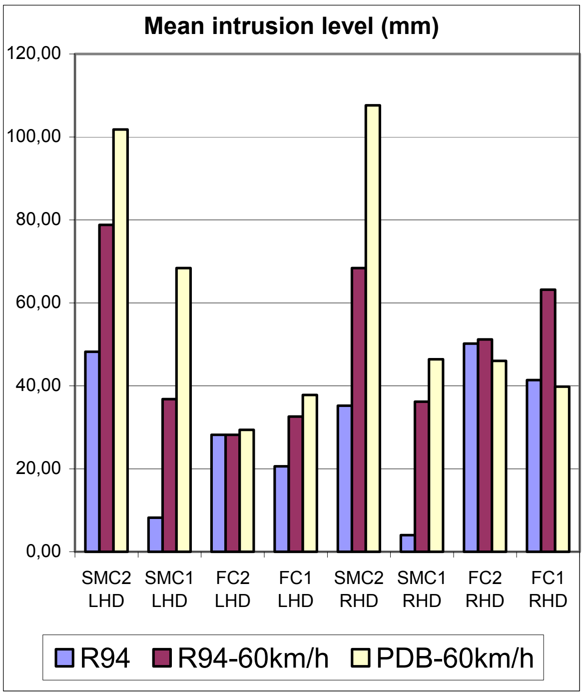


Figure 15: Intrusion level comparison

Passenger compartment acceleration

Theoretical approach is also confirmed regarding acceleration pulse ***(Figure 16)***. Stiffness of the PDB combined with protocol overlap generate higher acceleration pulse (without reaching the full width test pulse). The displacement distance with PDB is lower than ODB barrier that leads to higher deceleration pulse.

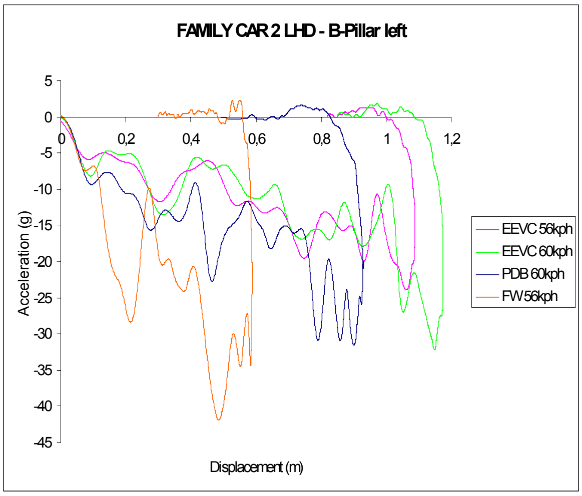


Figure 16: Acceleration pulses corresponding to a family car.

The mean acceleration information (g = delta V / t) is higher 20 % than current R94 ***(figure 17).*** Time duration depends on stiffness and mass. When the stiffness increases, the time duration decreases, the mass stays the same.

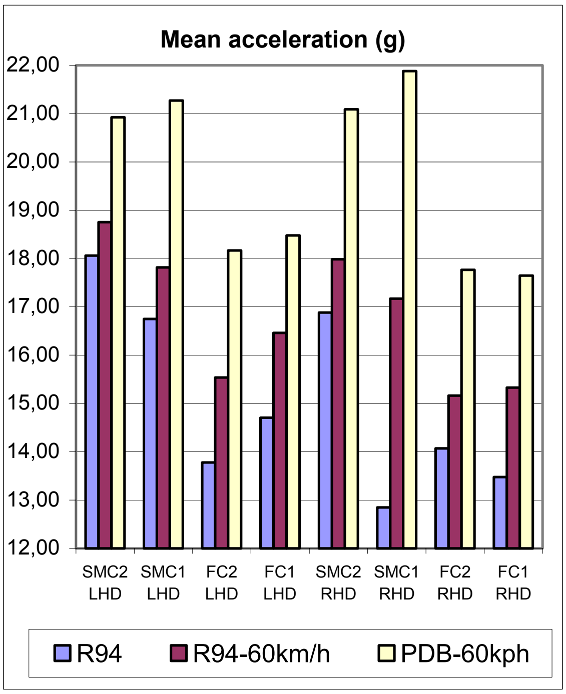


Figure 17: Acceleration level comparison

We have seen that PDB provides lower acceleration pulse than full width; however that test is able to generate in the same time acceleration and intrusion both parameters responsible for fatal and serious injuries ***(figure 18).*** This combination makes this test closer to real life accident.

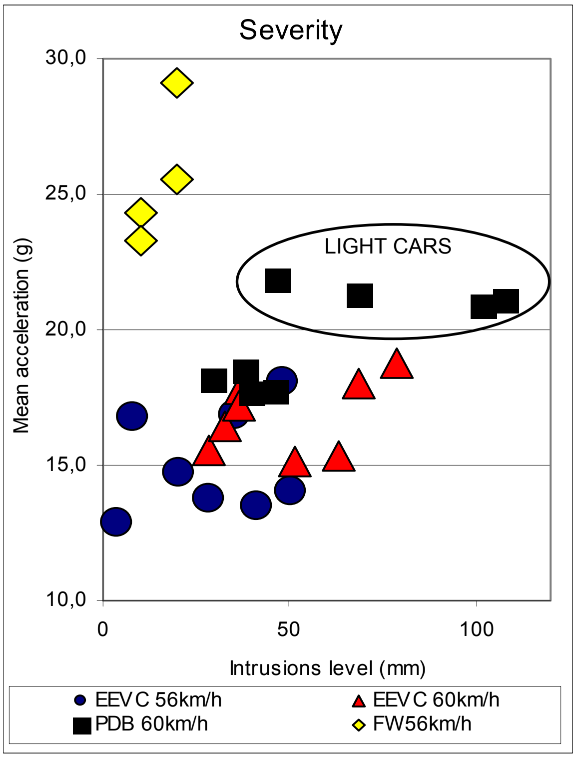


Figure 18: combination of intrusion and acceleration in the same time.

Dummy criteria

Even if dummies are not good tools to give an evaluation of severity due to dispersion, these one seams to confirm what we have seen before. PDB test can be severe for some categories of vehicles, especially old generations of light cars (that is going to disappear in a near future). A rating color classification has been used to illustrate the higher severity for a light car from the old generation ***a***nd a family car from the new generation ***(Figure 19)***.

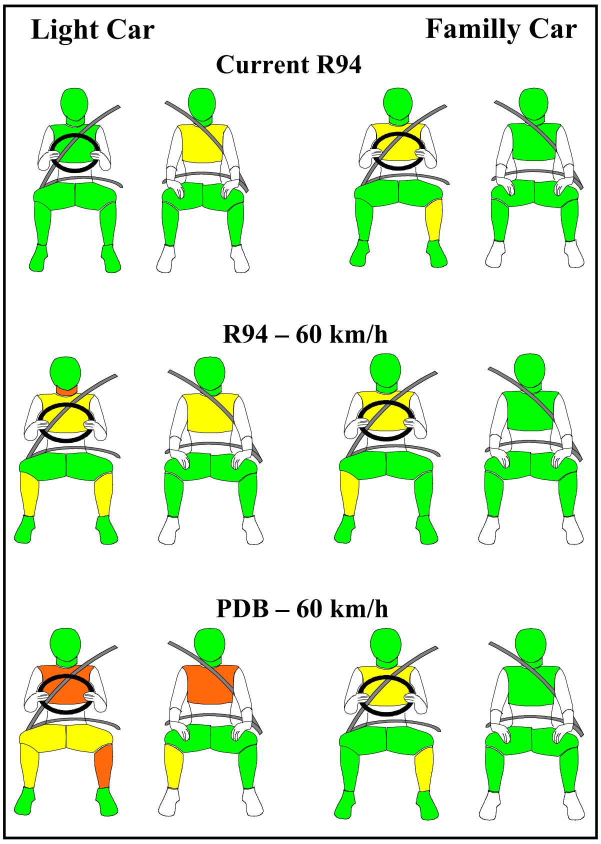


Figure 19: Dummies criteria for different offset test configurations.

However, recent generation of vehicles with high compartment strength, fitted with high performance restraint system is not sensible to this increasing severity (full data are available).

Partner protection analysis

In order to take advantage of all the potential for energy absorption of both cars, their structure must interact correctly. Limiting energy deficiency is now something that is generally accepted and leads to better structural interaction.

Barrier and front unit deformation comparison

Even if it is not the first priority, PDB definition allows checking and in the future assessing partner protection. In addition to test all vehicles at a more or less constant equivalent energy speed (EES), PDB is the ability to check the front unit aggressiveness. Bottoming out of the barrier face in case of stiffer front-ends of the larger vehicles is avoided as it is proved by tests performed ***(figure 21)***.

Figure 20: front deformation of 2000 kg family vehicle against current ODB barrier

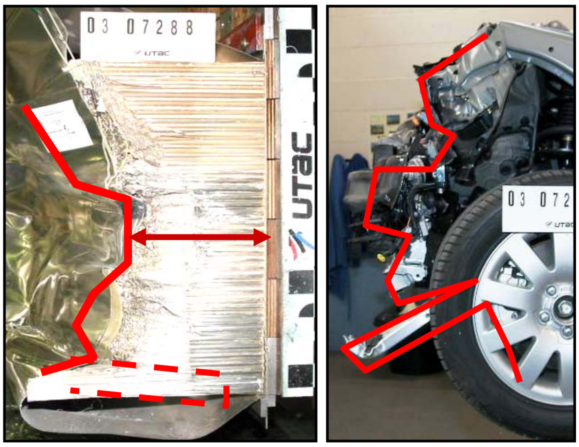


Figure 21: front deformation of the same family vehicle against PDB barrier

To reach the desirable intrusion level, the engine compartment has to absorb a certain amount of energy. Usually this is achieved through different load paths which absorb energy and transmit the load from the front to the occupant compartment. These load paths are designed and tuned against two types of obstacles: full width rigid barrier or soft deformable barrier. So far tests carried out on deformable barrier showed bottoming out phenomenon. This means that the front end design is not controlled by the barrier stiffness because the structure collapses with the help of the rigid wall behind the barrier. In all cases the obstacle is far from representing a car front unit. That's why structural behaviour in car to car accidents is different. Barrier shape is completely different; the current barrier deformation does not contribute to improve partner protection. No chance to detect front unit homogeneity, at the end of crash, all vehicle deformations are completely flat smoothed by the rigid wall (Figure 20 and Figure 22).

By which, front unit deformation resulting from PDB test is fully different. Bottoming out of the barrier face in case of stiffer front-ends of the larger vehicles is avoided. As it is proved by tests performed ***(figure 21 and figure 23)***.

Figure 22: front deformation against current ODB barrier of a super mini car

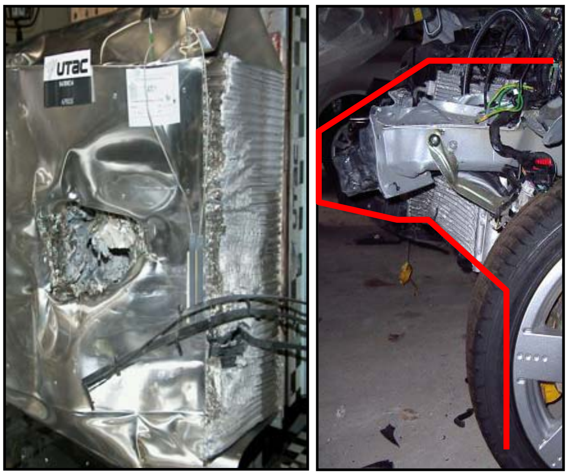


Figure 23: front deformation of the same super mini car against PDB barrier

Barrier analysis

PDB test procedure puts under control the energy absorbed by vehicle, the barrier is supposed to represent the vehicle we want to protect.
In the opposite of current offset test procedures proposed for compatibility assessment: car impact against weak deformable obstacle (with bottoming out phenomenon), the barrier deformation can be investigated. As we have seen before, against a rigid wall or soft barrier, the various load paths are not working the same way as they do in car to car interaction ***(figure 20 / 21- figure 22 / 23)***. The deformation process is at displacement dependant, whereas in car to car, the deformation is at pressure dependant. A car impact on a rigid wall might seem more simple: unfortunately it is not representative of a car front block and far from real world accident observations.
Current barrier can not be investigated, only the front face of the PDB barrier is able to give vehicle front end information (force and geometry).

Super Mini Car 2 *(Figure 24)*:
Weak and multiple load paths car do not penetrate the barrier. Forces are well distributed. Front deformation is homogeneous. Unfortunately, this soft stiffness design tends to disappear with self protection and reparability requirements.

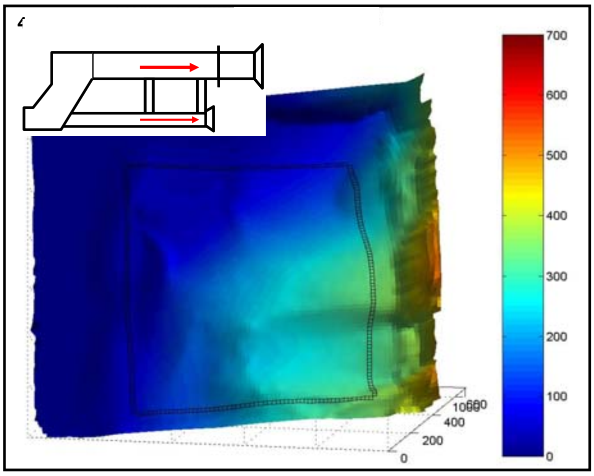


Figure 24: PDB deformation corresponding to the weak super mini car (SMC2) with lower load path

Super Mini Car 1 *(Figure 25)*:
Stiff longitudinal with weak cross beam penetrates the barrier. Forces are badly distributed. Cross member is not able to spread the force coming from the longitudinal. The surface in front of the load path is not in line with its stiffness. Deformation is unhomogeneous.

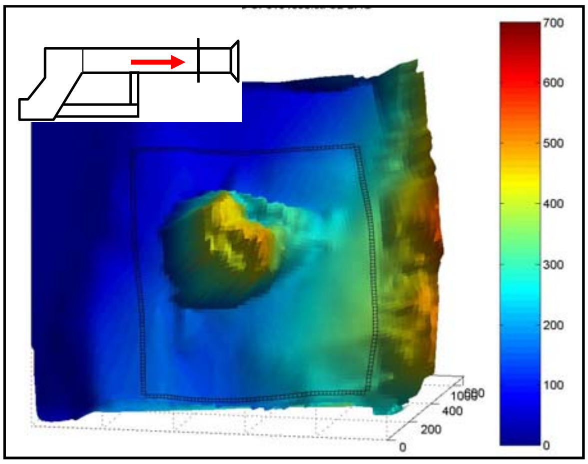


Figure 25: PDB deformation corresponding to the stiff super mini car (SMC1) without lower load path.

Family Car 2 *(Figure 26)*:
Forces generated by stiff longitudinal are well distributed by the cross beam. However, this one over crushed the barrier compare with lower load path. Front deformation is homogeneous in front of the cross beam, but quite inhomogeneous in height.

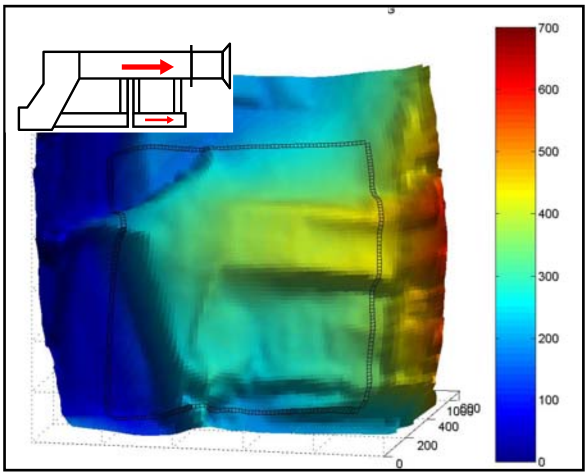


Figure 26: PDB deformation corresponding to the stiff family car (FC2) without advanced lower load path.

Family Car 1 *(Figure 27)*:
High forces generated by longitudinal and subframe are well distributed on a large surface. No over crushed between upper and lower load paths. Deformation is homogeneous.

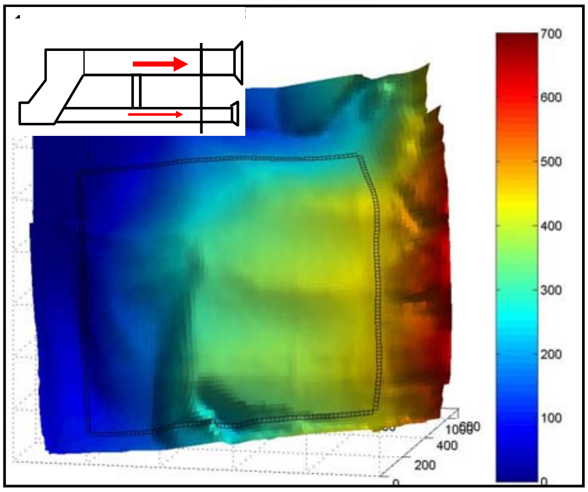


Figure 27: PDB deformation corresponding to the stiff family car (FC1) with advanced lower load path.

The PDB barrier is able to detect local stiffness but also transversal and horizontal links among load paths. The barrier records front cross member, lower cradle subframe, pendants linking position and stiffness that improve vehicles compatibility. That's why, assessment proposed for the future will be based on deformation because information is inside.

POSSIBLE ASSESSMENTS

As we have seen before, the test protocol allows checking simultaneously the two parts of compatibility:

- self protection coming from vehicle analysis and dummy criteria
- partner protection coming from barrier deformation

After having defining the test procedure and the obstacle, a set of relevant criteria have to be fixed in order to keep under control front end and passenger compartment design over the market production.

Self protection

Today, self protection assessment is very well known. According to current ECE R94 and EEVC WG16 proposal, assessment would be based on dummies criteria and intrusion measurements such as dashboard, firewall and A pillar ***(Figure 28)***.

Figure 28: Assessment comes from dummy readings and intrusion

Partner protection

The problem today is to find common criteria that will be representative of this phenomenon in order to put this item under control.
In term of design, one way to achieve structural interaction is to offer a front surface which is homogeneous in stiffness over a surface which is large enough. To illustrate this point, we have to imagine that we put a rigid plane between both cars. The concept of the wall is to have a homogenous stiffness over a large surface. To achieve this result, the stiffness on the front block must be distributed along multiple load paths. Having this is not enough, as they cannot ensure that the stiffness is homogeneously spread over the front surface.
The PDB deformation already showed its capacity to verify the behaviour of new vehicles in regard to the partner protection targets. There is an assessment

(PPAD) calculated by PDB software that can be loaded from the EEVC WG15 Website. However, this assessment is not yet ready to be introduced as partner protection criteria.

Investigation area

Investigation area is different from the recorded area represented by the total front PDB surface.
According to geometrical measurements of European fleet and essential load paths needed for good structural interaction (upper rail, cross beam and subframe), the investigation area was fixed between 200 mm and 700 mm ground clearance in height (Z axis) ***Figure 29 / 30***.
In Y axis, the area depends on the width of the vehicle. To avoid boundary effects, 100 mm margin in left and 150 mm in right are applied for LHD, the opposite for RHD.

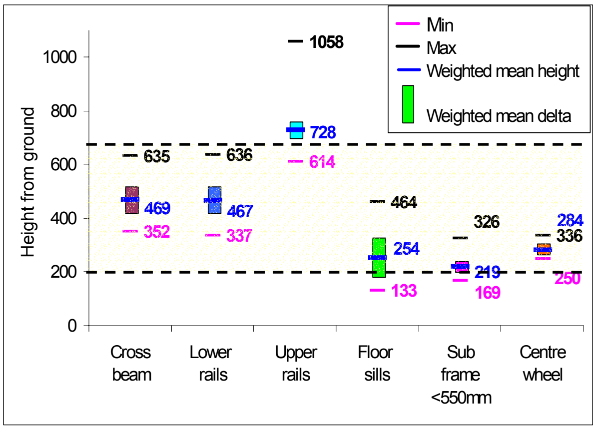


Figure 29: Geometrical data (ground clearance) of 70 % of the European fleet

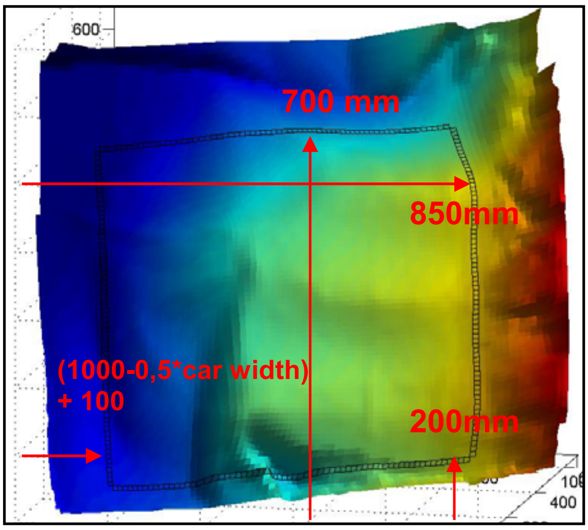
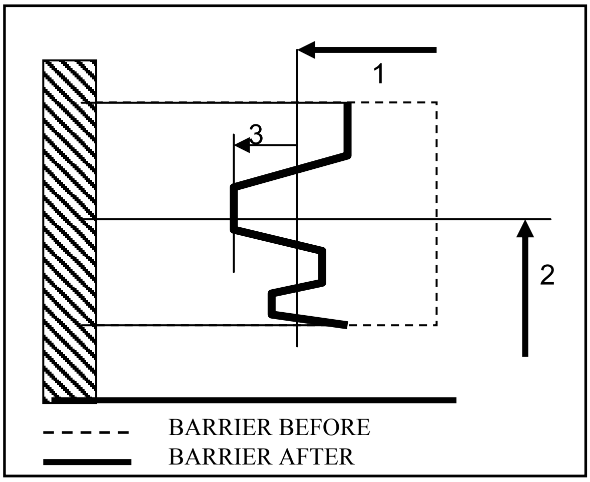


Figure 30: Investigation area.

Possible basic criteria (mid term)

The current formula given by the PDB Software V1.0 that we have seen before is little bit difficult and mix geometry effects as well as stiffness effects without dissociating both. That's why; we propose a comprehensive approach, separating geometry from stiffness.



1- ADOD: Average Depth Of Deformation
2- AHOD: Average Height Of Deformation
3- HP: Homogeneity Parameter

Figure 31: possible partner protection parameters

Results show that AHOD are less sensible to the tested car and similar to AHOF approach. ADOD is link to the front stiffness of the car and rise up with the mass. HP is supposed to detect local penetration in the front barrier face that indicates bad homogeneity. First results seem to confirm that using average could be the wrong direction.
However, it is too early to introduce a partner protection assessment. Further working is required before proposing a set of criteria.

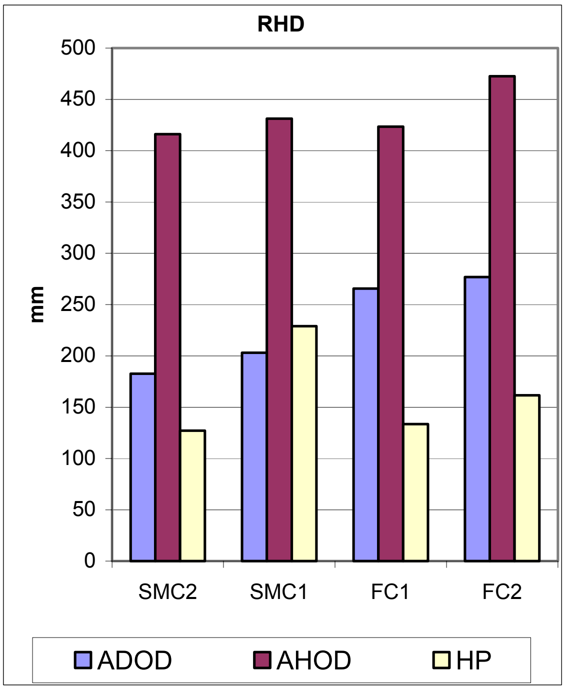


Figure 32: AHOD, ADOD and HP in Right Hand Drive.

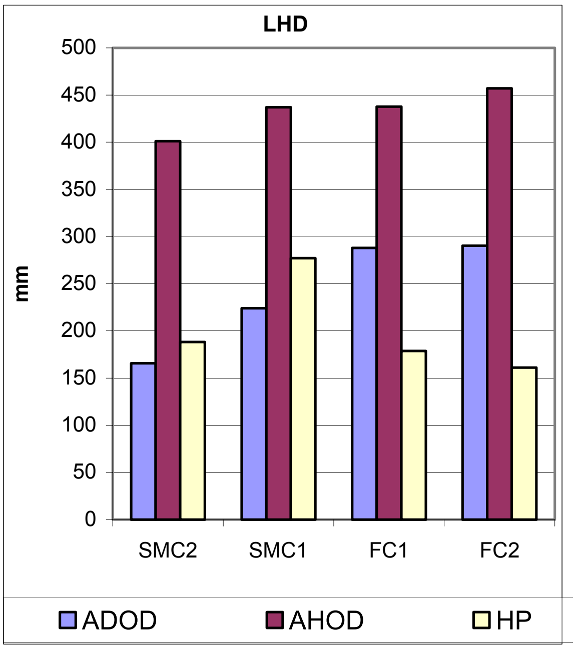


Figure 33: AHOD, ADOD and HP in Left Hand Drive.

Left hand drive and Right hand Drive results are very close; the PDB face deformation is not so much influenced by the driving position and tested side, in other words, by the gear box and engine position.

Future working

These tests will be accompanied with a car-to-car test in order to validate the PDB deformation.
Due to the necessity of self-protection and the wide range of vehicle's size, mass and stiffness, we have to define and fix a limit for compatible design.

POSSIBLE STEPS FOR PROGRESSIVE COMPATIBILITY INTRODUCTION (Figure 34)

First step solution- short term- : Improving and harmonize Self Protection level

As a first step, the French proposal is to replace the current ODB barrier by the PDB one in regulation. The first effect of the progressive barrier is the ability to test all vehicles at a more or less constant equivalent energy speed (EES). In this first phase, assessment remains focused on self-protection. PDB barrier introduction will be able to improve self protection of light vehicles (overloaded) without increasing heavy ones due to energy capacity absorption. The test severity is in line with the speed proposed by the EEVC WG16, higher than the current European regulation (56kph) and fixed for all cars

Self protection is already assessed for a long time from dummy criteria. The proposal suggests adding intrusion level investigation.
Dummies criteria limits are the same than the current ECE R94 and integrity of the passenger compartment could be assess with the help of intrusion level in different part of the front compartment.

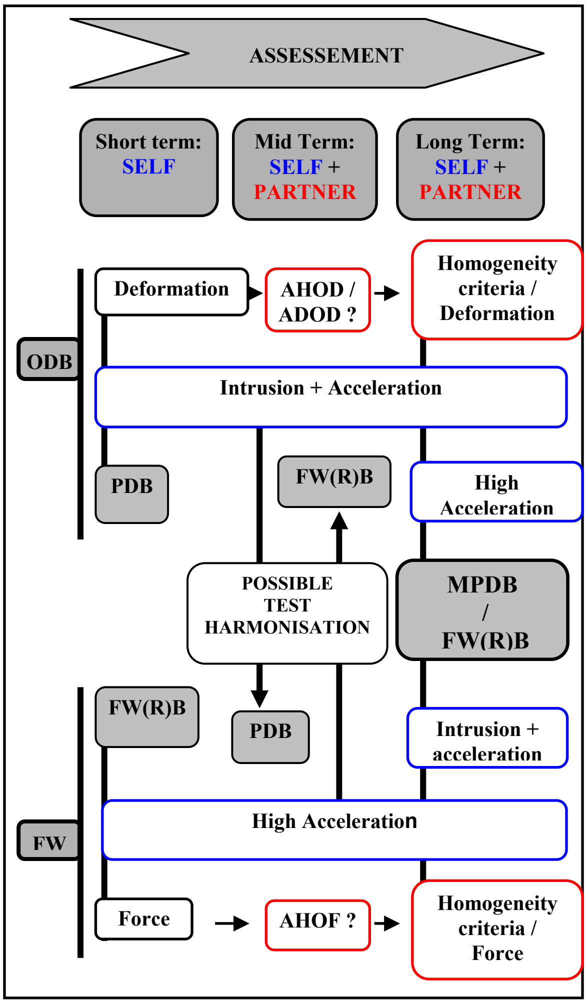


Figure 34: Possible steps towards compatibility harmonisation

Second step solution -mid term- : Partner protection introduction

We hope that partner protection will be ready at this time. All criteria and investigations will be based on the barrier deformation. PDB barrier is able to detect local stiffness but also transversal and horizontal links among load paths. It looks like car to car accident or test analysis, except that in this case, the barrier deformation is investigated instead of the car's. An aggressive vehicle would be identified by large and non homogeneous deformation.
Furthermore, this proposal could generate higher deceleration pulse combined with higher intrusion. However, further researches are necessary.

Third step proposal- long term- : introducing Mobile PDB

To be closer to real life accident, the PDB could be fixed on a mobile trolley as Australia investigated three years ago. A quick energetically approach clearly shows than this test due to conservation of momentum associated to different energy absorbed in the barrier allows to progressively switch from a light car overload to a heavy car partner protection test. However and before proposing this test as a regulation, we have to investigate it.

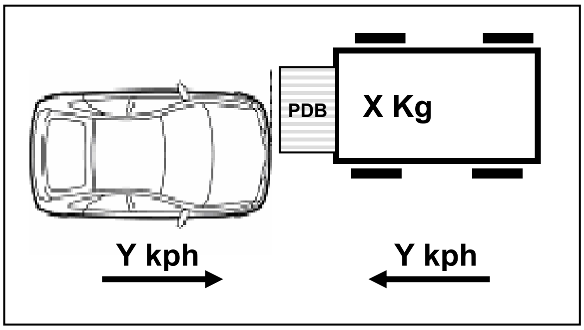


Figure 35: Possible long term proposal

CONCLUSION

After having compared the different offset test proposed, considered current and future generation of cars in Left Hand Drive and Right Hand Drive, it appears to us that test with current barrier is not adapted to new compatibility requirements.
It conducts to an inhomogeneous fleet due to non adapted deformable element. Furthermore, rising up test speed without changing deformable element could become very dangerous for compatibility issue and does not represent an answer for heavy / light vehicle compartment strength harmonisation. Furthermore, current barrier deformation does not allow investigating partner protection.

Harmonisation of offset test severity is considered by several passive safety experts as the main priority, the most effective way and probably the first step towards compatibility. Unfortunately, as we have seen before, unstable obstacle, bad reproducibility and bottoming out make tests with current barrier far from this objective. That's why, the replacement of the current deformable barrier by the PDB one is becoming the first priority. On the same time, checking light car compartment strength is proposed; test speed would be fixed at 60 km/h corresponding to WG16 suggestion.
This proposal would be able to check both self and partner protection and easy to introduce as a regulation.
However, in a first step, only self protection will be assessed. It is too early to introduce partner protection assessment, criteria are not yet ready. Further investigations are needed; several international task forces are working in that direction.
However, aggressiveness assessment is achievable from the barrier deformation. The studies in progress confirm that statement. The concept, close to real life car to car collision clearly shows the capacity of the front unit to be aggressive or not. A basic assessment could be introduced in a second step.

The development of future vehicles with respect to these targets would result in a compatible fleet. Moreover, considering the time taken to renew all the vehicles, it is necessary to propose measures that change too often to avoid rupture in the fleet.
To conclude, even if the PDB offset test doesn't generate high deceleration pulse, test procedure is fully representative of real world accident because it combines acceleration and intrusion and would become a restraint-system dimensioning test associated with intrusion.

AKNOWLEGDEMENTS

The study presented in this paper was in part supported by Renault SAS and PSA Peugeot-Citroën. We wish to thank French car manufacturers for their cooperation.

REFERENCE

1 VC Compat (Car and trucks leg) activities

2. EEVC / WG 15 activities

3. EEVC / WG16 activities

4. IHRA frontal group activities

5. PDBsetupV10 application can be loaded from the EEVC WG15 Website (www.eevc.org)

6. PDB test procedure V2-2 can be loaded from the EEVC WG15 website (www.eevc.org)

STUDY OF LOAD CELL MDB CRASH TESTS FOR EVALUATION OF FRONTAL IMPACT COMPATIBILITY

Satoshi Takizawa
Eisei Higuchi
Tatsuo Iwabe
Honda R&D Co., Ltd.
Takayuki Kisai
Takayuki Suzuki
PSG Co., Ltd.
Japan
Paper Number 05-0235

ABSTRACT

The purpose of this study is to evaluate load cell moving deformable barrier (LCMDB) tests as a means of assessing frontal impact compatibility between vehicles. An LCMDB is employed to enable assessment of relevant partner-protection characteristics in addition to self-protection performance in a front-to-front crash test. The ability to control key characteristics of compatibility in LCMDB tests enables force measurements on the load cell wall to be used to assess structural interaction, frontal force level and passenger compartment strength.

In this study, LCMDB tests have been conducted with various deformable elements to determine how well they correlated with fixed barrier tests or vehicle-to-vehicle tests. Firstly, barrier load cell data measured in a full-frontal LCMDB-to-vehicle crash test are compared with data measured in a full width deformable barrier (FWDB) test at 56 km/h. In addition, some compatibility metrics such as average height of force (AHOF) and force distribution are compared. Secondly, an offset-frontal LCMDB-to-vehicle crash test has been conducted to evaluate the passenger compartment strength for small cars in an overload condition. Force measurements of the load cell wall are compared with data obtained from an offset deformable barrier (ODB) test at 64 km/h. Finally, an oblique-frontal LCMDB-to-vehicle crash test has been conducted and the test results are compared with vehicle-to-vehicle tests and with fixed oblique barrier tests at 50 km/h in terms of the vehicle and occupant kinematics.

The study has shown that the LCMDB-to-vehicle test offers a realistic simulation of the effect of differences in mass in vehicle-to-vehicle impacts, and enables compatibility metrics to be evaluated.

INTRODUCTION

Frontal vehicle-to-vehicle collisions are still the most common accident type causing fatal or serious injuries; hence vehicle crash compatibility in frontal impact may offer the greatest potential to enhance a vehicle occupant’s safety. One of our research goals for enhancing frontal impact compatibility between vehicles is to develop new test procedures which would lead vehicle structures to be more compatible in frontal collisions. Compatibility performance is determined both by self-protection performance and aggressivity; therefore compatibility assessment must have test methods and performance criteria for these two requirements. The authors examined a set of test procedures for frontal impact compatibility to evaluate relevant vehicle characteristics of compatibility including a moving deformable barrier (MDB) test method [1, 2]. The MDB test is currently one test method used to simulate vehicle-to-vehicle crashes from the dual perspective of body deceleration characteristics, which control occupant injury severity, and occupant compartment space. The MDB test allows the mass ratio effect to be taken into account, and it can generate a realistic delta V and vehicle deceleration pulse. The approach of using an MDB test can produce relatively realistic vehicle-to-vehicle crash response, deformation and occupant kinematics, thus the MDB more adequately represents what happens in vehicle-to-vehicle type accidents. The work described in this paper updates the MDB test method with data obtained from employing a load cell MDB (LCMDB) to evaluate relevant characteristics for frontal impact compatibility. The ability to control key characteristics of compatibility in LCMDB tests enables force measurements on the load cell wall to be used to assess structural interaction, frontal force level and passenger compartment strength. This paper provides a comparative analysis between the fixed barrier tests and the LCMDB tests. Three major fixed barrier test conditions were selected based on commonly conducted international crash testing, which are the full width deformable barrier (FWDB) test, offset deformable barrier (ODB) test and fixed oblique barrier (FOB) test.

MDB-TO-VEHICLE FULL-FRONTAL CRASH TESTS

In the US fleet, incompatibility between LTVs and passenger cars has been identified through an accident analysis [3]. One issue of the incompatibility between LTVs and passenger cars is based on a lack of structural interaction due to geometrical differences. Barrier load cell data in the US New Car Assessment Program (US-NCAP) was investigated by the National Highway Traffic Safety Administration (NHTSA), and some compatibility metrics such as the AHOF, initial force and force distribution were measured on the load cell wall (LCW) [4, 5]. Those parameters may control structural interaction and frontal stiffness, which would be beneficial in enhancing the interaction characteristics of vehicles. Therefore, a full width barrier test with a load cell wall could be a candidate test procedure to evaluate the interaction characteristics and stiffness (sometimes referred to as the “aggressivity” of vehicles). A number of parameters can be proposed and developed from the available barrier load cell data. The Transport Research Laboratory (TRL) developed a full width deformable barrier (FWDB) test and some homogeneity criteria were proposed to assess and control structural interaction. Figure 1 shows the configuration of the FWDB. Currently the deformable barrier face that is proposed by TRL has two layers. The first layer consists of a 0.34 MPa aluminum honeycomb element that is 150 mm deep, and the second layer consists of a 1.71 MPa element, also 150 mm deep. The second layer is segmented into individual blocks and is constructed so that each block is in line with each barrier load cell.

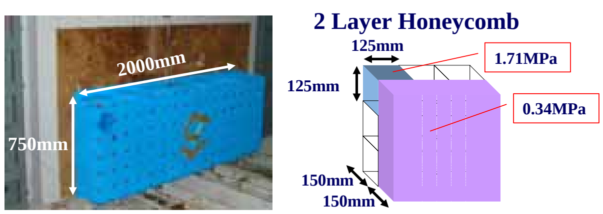


Figure 1. Full width deformable barrier test

The purpose of full-frontal LCMDB testing with the 2 layer honeycomb is to compare it with the FWDB test using measured compatibility metrics. In this study, the weight of the LCMDB was set to the same weight as the target vehicle in order to compare the test results with the FWDB test. Figure 2 shows the load cell layout of the full-frontal LCMDB test. The LCW for the MDB full-frontal impact consists of 64 load cells, with each surface area 125 x 125 mm. Unfortunately the number of the load cells was restricted by the gross weight of the LCMDB. The mass of the LCMDB was set to correspond to the subject SUV, which was about 2200 kg.

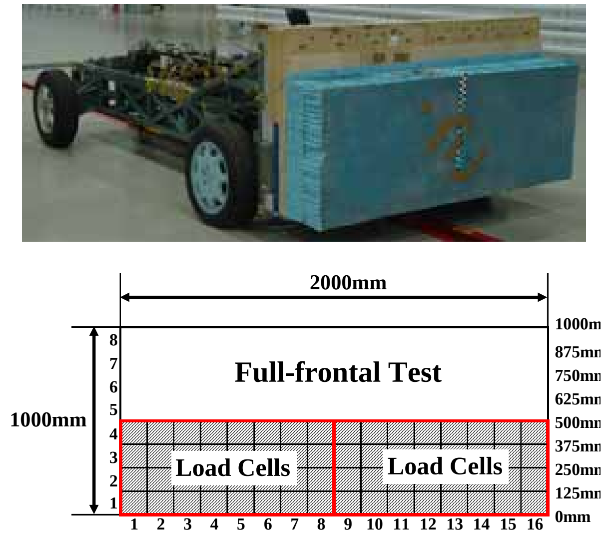


Figure 2. Load cell moving deformable barrier layout

The ground clearance of the load cell wall for the LCMDB was set at 205 mm in height in order to get the barrier load data generated by the primary energy absorption structure (PEAS) and secondary energy absorption structure (SEAS). The 64 load cells covered the US bumper regulation zone and the height of the load cells was in line with the 2nd-5th row of the fixed barrier’s LCW. See Figure 3.

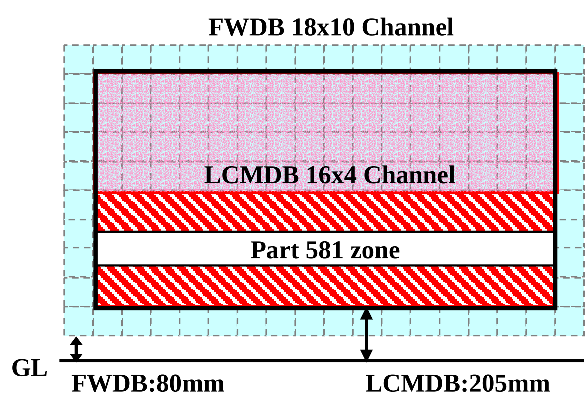


Figure 3. Comparison of load cell layout

The test program was developed with the objective of evaluating the use of an LCMDB constant energy compatibility test procedure in comparison to the FWDB test. Figure 4 compares the full-frontal impact tests among three different test configurations. In LCMDB-to-vehicle testing with a shallow deformable barrier (DB), the impact speed should be adjusted so that the kinetic energy corresponds to the vehicle-to-vehicle impact due to the shallow DB lacking an energy absorption capability. An energy equivalent full-frontal LCMDB test was conducted and the test results were compared with the FWDB test. An SUV was selected as a target vehicle to analyze barrier load cell data. An LCMDB-to-SUV impact was performed at a closing speed of 80 km/h to maintain the kinetic energy, which was equivalent to that at the FWDB 56 km/h. Hybrid III 50th percentile male dummies were used to study the injury levels for the driver and passenger positions.

Test Configuration

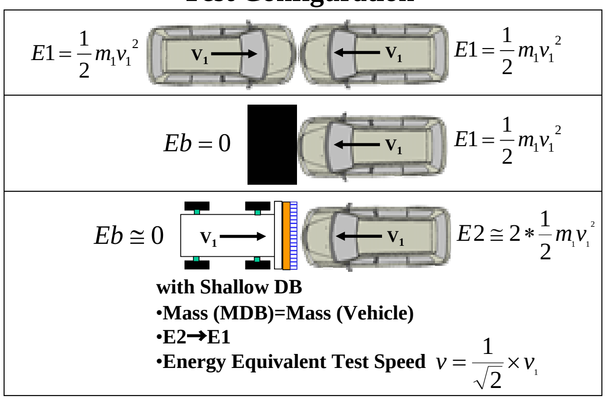


Figure 4. Energy equivalent full-frontal impacts

The deformation levels of the vehicles demonstrated similar results except slightly different deformation modes of the front side member. See Figure 5.

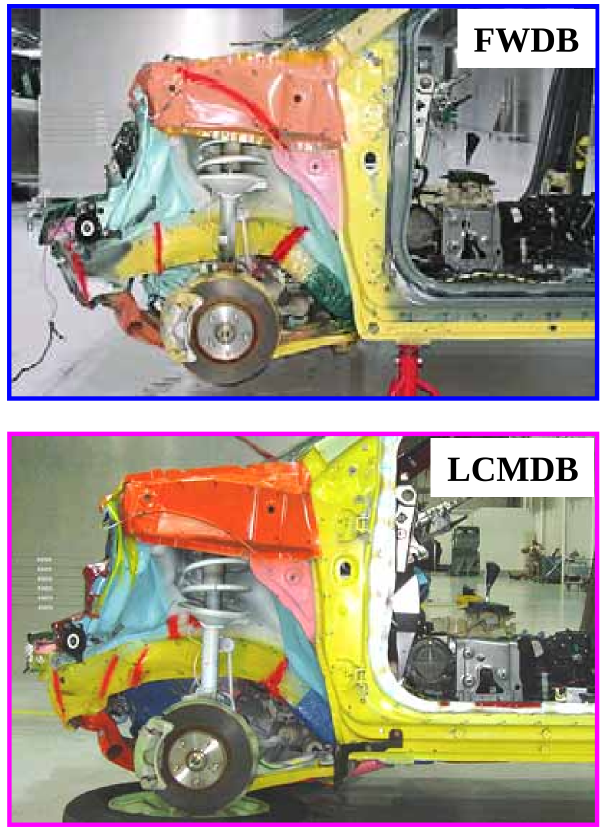


Figure 5. Comparison of body deformation modes

Figure 6 shows dummy injury levels. Similar results were also observed between the two tests.

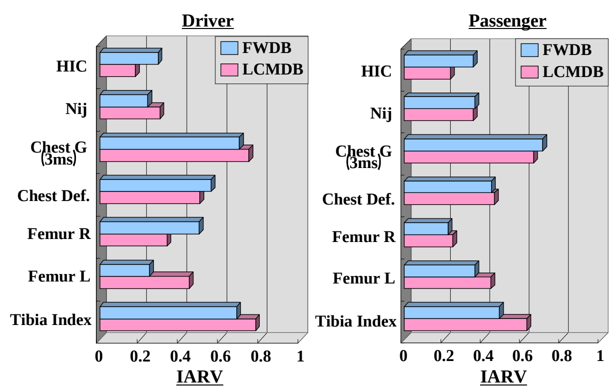


Figure 6. Comparison of injury measurements

Noticeable differences between the two tests occurred on the deceleration-time histories. The vehicle deceleration pulse in the energy equivalent LCMDB test indicated shorter duration of the crash pulse compared with the FWDB test. See Figure 7.

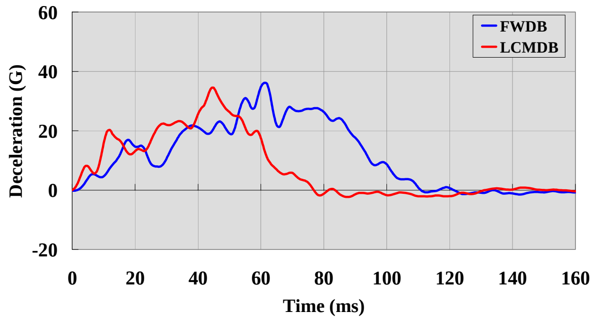


Figure 7. Comparison of body deceleration vs. time curves

Compared to the vehicle deceleration pulse, the dummy deceleration pulses in the LCMDB test demonstrated shorter crash pulses than were achieved in the FWDB test while the injury values were similar. Figure 8 shows the dummy chest deceleration pulse as an example of the dummy response.

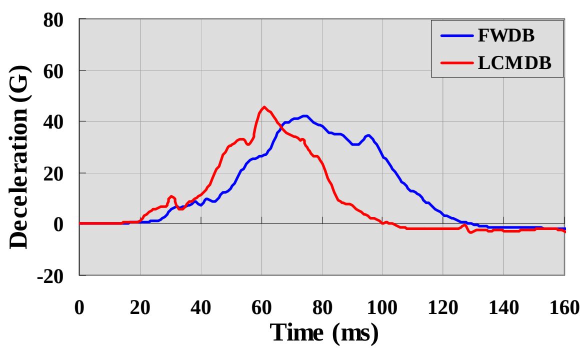


Figure 8. Comparison of chest deceleration pulses of driver dummy

An interesting comparison can be made by inspection of the deceleration vs. displacement curves. The two deceleration-displacement curves follow each other quite closely until the end of the impact. This illustrates the overall structures were behaving in a similar way in both tests, which equates to reproducibility, which is a prime requirement for an energy equivalent test. See Figure 9.

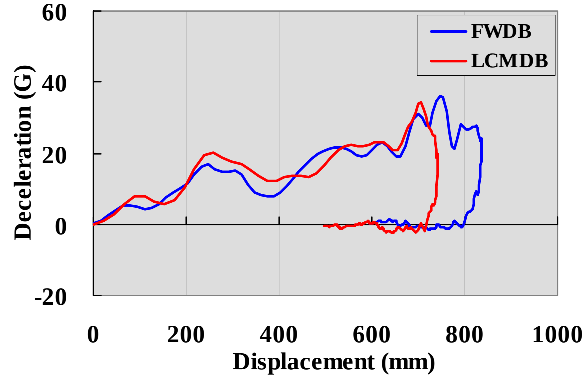


Figure 9. Comparison of body deceleration vs. displacement curves

In principle, the vehicle deceleration pulse determines the relative movement between the vehicle and the dummy. The dummy displacement relative to the vehicle generates a tension force on the seatbelt and the dummy deceleration is produced by the seatbelt tension force. The deceleration-displacement curves for the driver pelvis clearly proved this theory. See Figure 10.

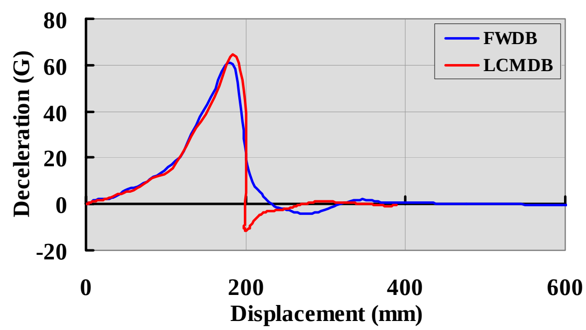


Figure 10. Comparison of dummy pelvis deceleration vs. displacement curves

However, the deceleration curves for the driver head were different between the two tests. See Figure 11. This may be because an airbag reaction force, which is determined by the internal pressure of the airbag, is dependent on time; whereas the seatbelt tension force is dependent on displacement as a factor. In an energy equivalent LCMDB test, the deceleration vs. time histories should be checked if such data would influence test results.

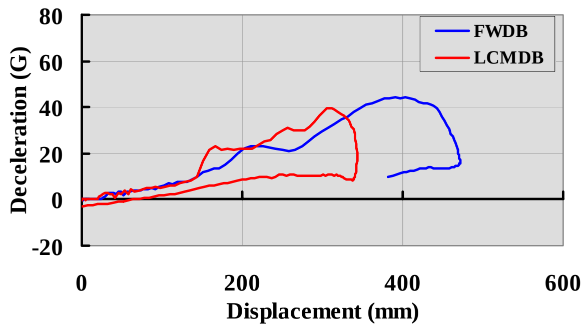


Figure 11. Comparison of dummy head deceleration vs. displacement curves

Next, the barrier load cell data was compared between that obtained in the FWDB test and that in the LCMDB test. Fairly good correlation was seen in the total barrier load cell data. See Figure 12.

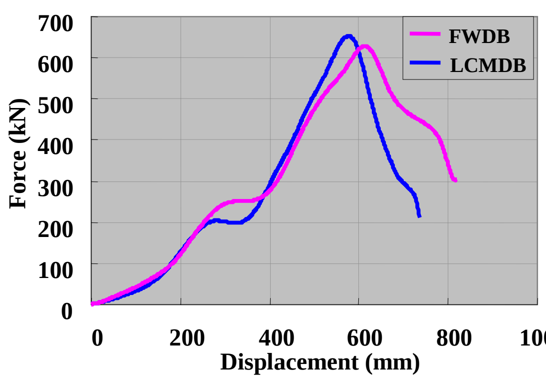


Figure 12. Comparison of total barrier force

Moderate correlation was seen between the two barrier load cell data sets; however, the major differences in the load cell data were caused by the bottoming out of the deformable barrier in front of the side members. See Figure 13.

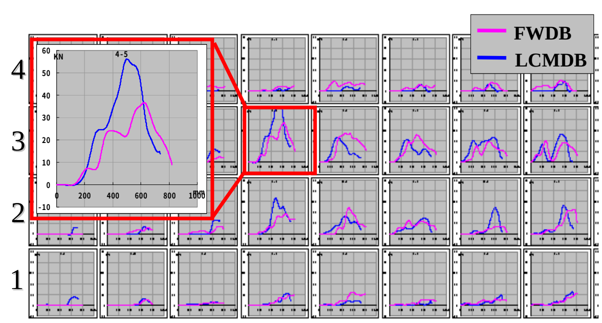


Figure 13. Comparison of barrier force in each load cell (left side), Force (kN) vs. Displacement (mm)

The time-based contour graphs were compared between the two tests. Considerably different contour graphs were seen in the time-based graph. See Figure 14.

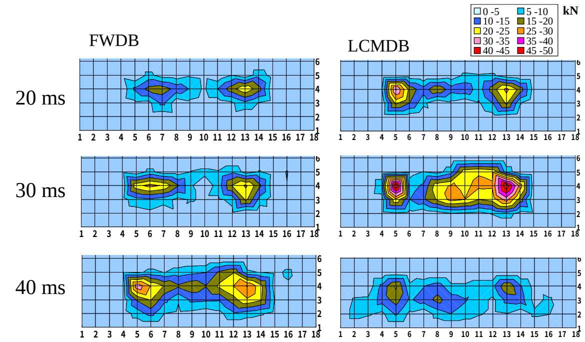


Figure 14. Comparison of time-based contour graphs

However, displacement-based contour graphs illustrated more similar results due to similar deformation modes of the body. See Figure 15. Therefore, barrier load data analysis was made in the displacement-based barrier load data in addition to the time-based load cell data analysis in this energy equivalent test.

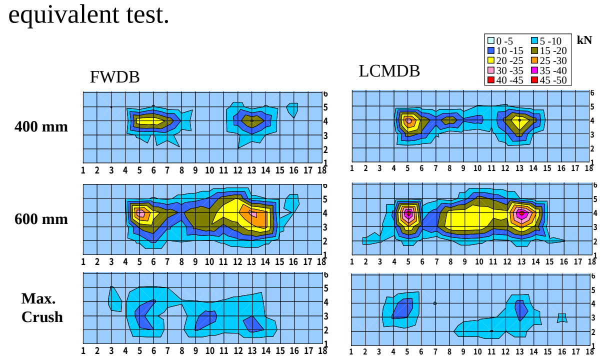
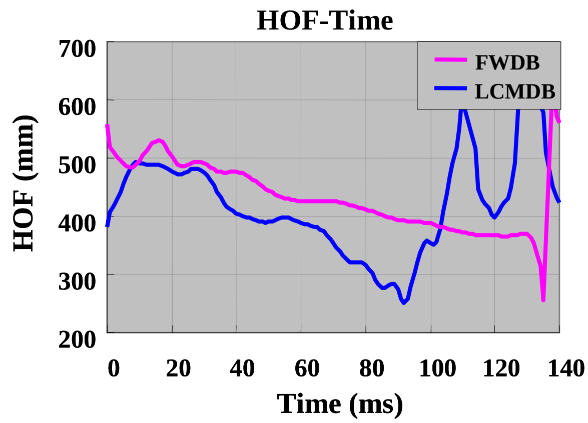


Figure 15. Comparison of displacement-based contour graphs

The height of force (HOF) was computed for each time step and for each displacement step during the impact. The HOF-displacement graph in the LCMDB test looks similar to that in the FWDB test compared with those in the HOF-time graph. Moreover the HOF-displacement graph visually told us what structure has influenced the HOF during the impact. As can be seen in the picture, the engine loading might have decreased the HOF. See Figure 16.

$$HOF(t) = \frac{\sum_{1}^{cells} Fi \times Hi}{\sum_{1}^{cells} Fi} \qquad t: \text{Time step}$$



$$HOF(d) = \frac{\sum_{1}^{cells} Fi \times Hi}{\sum_{1}^{cells} Fi} \qquad d: \text{Displacement step}$$

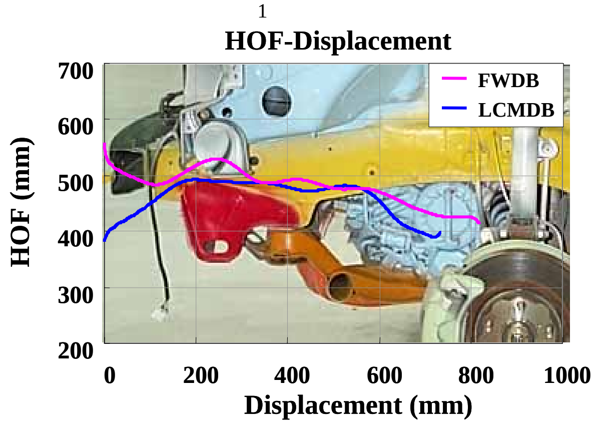
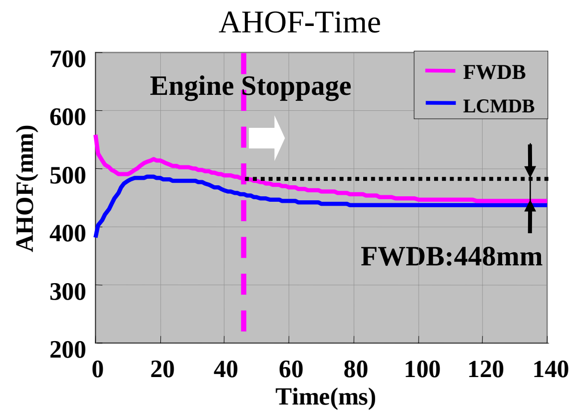


Figure 16. Comparison of height of force (HOF)

$$AHOF = \frac{\sum_{0}^{t} HOF(t) \times F(t)}{\sum_{0}^{t} F(t)}$$



$$AHOF = \frac{\sum_{0}^{d} HOF(d) \times F(d)}{\sum_{0}^{d} F(d)}$$

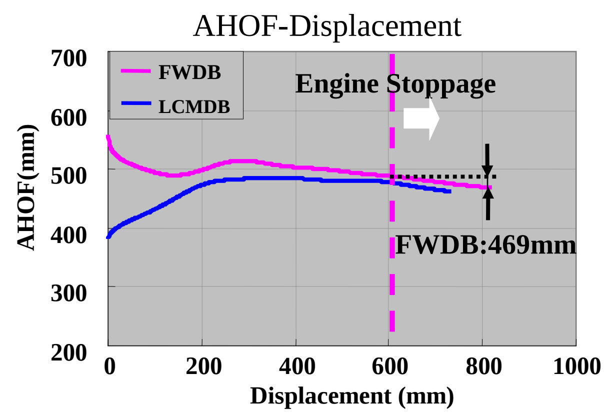
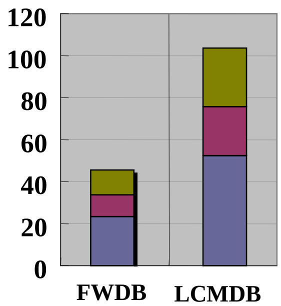


Figure 17. Comparison of average height of force (AHOF)

The average height of force (AHOF) is computed using the force data as a weighting function. Barrier forces transmitted through the engine may have greater influence on time-based AHOF because the time after engine stoppage was relatively long. On the other hand, displacement-based HOF may have less of an influence on engine loading because the displacement after engine stoppage was relatively short. In fact the time-based AHOF in the FWDB test indicated a 21 mm lower value than that of the displacement-based AHOF in the same FWDB test. See Figure 17. The displacement-based AHOF may reduce the influence on the engine loading and this could be more beneficial in assessing structural interaction or geometry to enhance compatibility.

The Homogeneity Assessment proposed by TRL was computed to investigate the correlation between the two tests from a force distribution viewpoint [6]. This approach is developed to assess the homogeneity of forces in a vehicle foot print. Although the force distribution looks similar in the bar charts, the homogeneity assessment in the LCMDB test was twice as large as that in the FWDB test. See Figure 18. Haenchen et al. pointed out the issue of the impact alignment sensitivity of vehicles when the LCW data is used in compatibility assessments [7]. When concentrated loadings hit the junction between multiple load cells, those loadings are spread over several load cells. This may create a more homogeneous force distribution and may result in an advantageous assessment value. Because of the potential for the impact sensitivity of the load cell wall, repeatability tests will be necessary to check deviation in the homogeneity assessment of both FWDB tests and LCMDB tests.

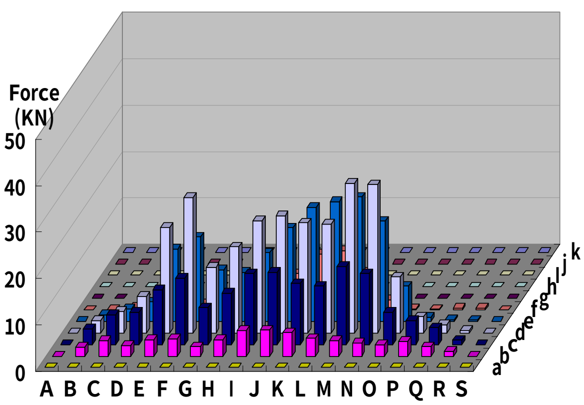
Homogeneity Assessment



	FWDB	LCMDB
Vc	23.3	52.4
Vr	10.5	23.4
Vcl	11.8	27.8
V	45.5	103.6

Vc : Cell Variance
Vr : Row Variance
Vcl : Column Variance

FWDB Smoothed Data



LCMDB Smoothed Data

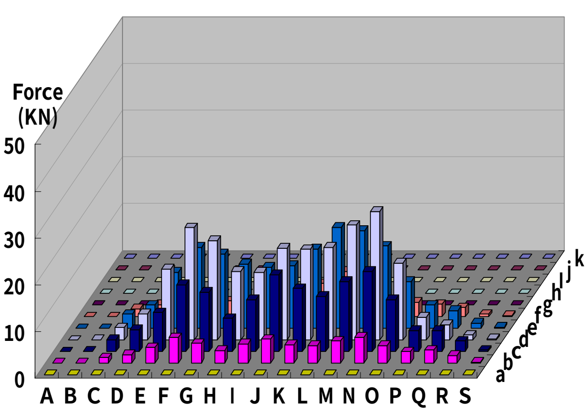


Figure 18. Comparison of homogeneity assessment

MDB-TO-VEHICLE OFFSET-FRONTAL CRASH TESTS

Generally speaking, when small vehicles are crashed into large vehicles, small vehicles experience harsher damage. Therefore, passenger compartment strength and deceleration levels are most significant for small vehicles in enhancing their self-protection performance. Apparently, providing survival space in collisions is a very important requirement for passenger compartments. Thus a passenger compartment strength test is needed to assess the passenger compartment strength to determine whether it is strong enough. An 80 km/h ODB test for passenger compartment strength has been proposed by TRL that uses a load cell wall (LCW) to assess the force generated by the vehicle [7]. However, the 80 km/h ODB test with the LCW is simply designed to measure the passenger compartment strength, and does not require instrumented dummies. What seems to be lacking is consideration of the injury mechanism during impact. Measurement of the passenger compartment strength alone may not be enough to assess injuries because injury levels are not only determined by maximum intrusion, but are also determined by the deceleration pulse. Naturally, instrumented dummies can detect the correct injuries.

An LCMDB test to assess self-protection performance may provide more realistic overload conditions compared to the 80 km/h ODB test. An offset-frontal LCMDB-to-vehicle test, with closing speed of 100 km, was conducted between the LCMDB and small vehicles with a mass ratio of about 2.0. Small vehicles could use this approach to help comply with passenger compartment strength requirements. In our previous study, nothing reproduced the deceleration pulses generated in vehicle-to-vehicle impacts better than the MDB test. As a consequence, the LCMDB-to-vehicle test could be a candidate procedure for assessing passenger compartment strength and the deceleration pulse.

Development of deformable barrier

In order to simulate a vehicle-to-vehicle impact, it is necessary for the DB to approximate the crush characteristics of actual vehicles. In this research, the use of the load cell data obtained from a FWDB test was used to make a custom-built DB that consisted of aluminum honeycomb elements. The force-displacement (F-D) characteristics in the FWDB test were transformed into the pressure-displacement (P-D) characteristics. Total barrier force was divided by the load cell area to generate a P-D curve. The P-D curve was the basis for assigning crush characteristics to the DB. The P-D characteristics of the DB for this study approximate the stiffness of large vehicles, which progressively increase in the pressure from 0.3 MPa to 0.7 MPa with 700 mm of crush depth to prevent bottoming out. See Figure 19.

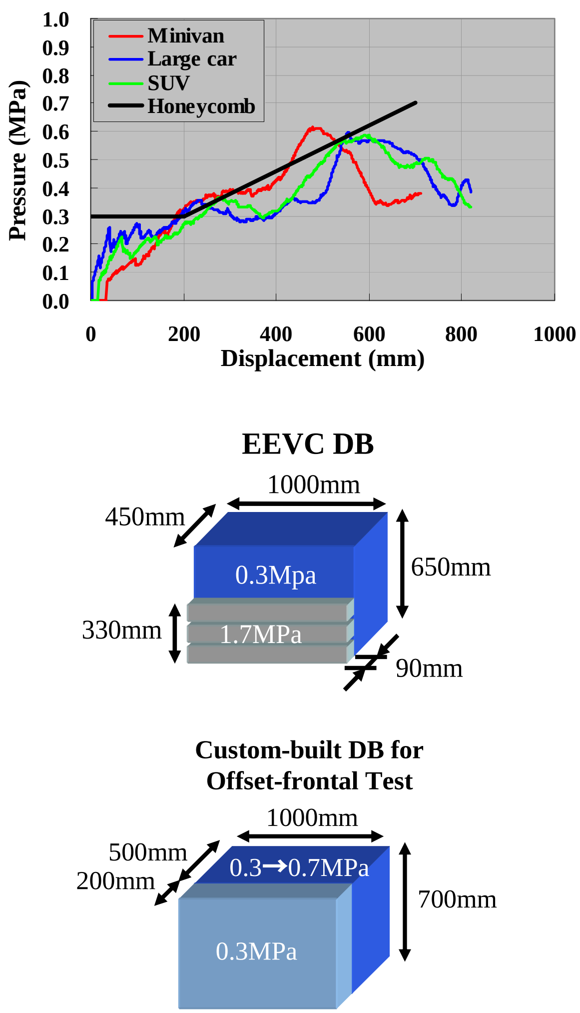


Figure 19. Pressure-Displacement Curve for LCMDB

LCMDB-to-vehicle offset-frontal impact

After the deformable barrier was developed, an LCMDB-to-vehicle testing was conducted to analyze load cell data. Figure 20 shows the layout of the load cells which are attached to the MDB. For an offset-frontal LCMDB impact, 64 load cells are arranged in an 8x8 matrix.

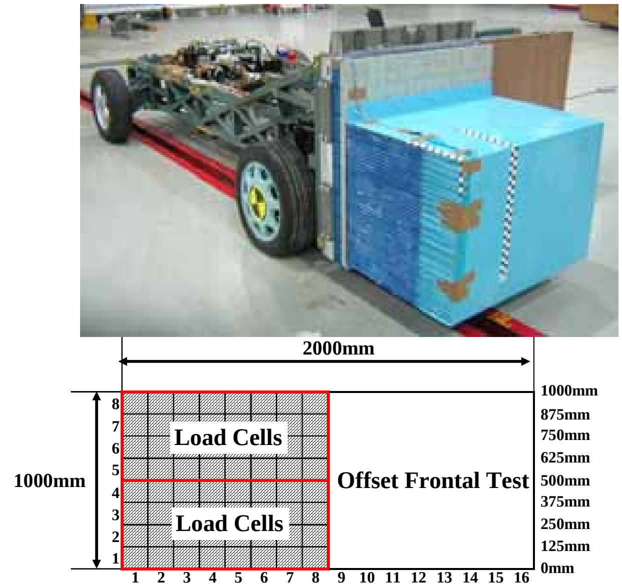


Figure 20. Load cell layout for offset frontal test

An LCMDB-to-vehicle impact was conducted to determine how well such an impact compared to vehicle-to-vehicle impact with a small car, to overload the passenger compartment and investigate its deformation resistance. The LCMDB weight was set to correspond to the modeled vehicle representing an SUV. The LCMDB was crashed into a compact sedan at 40% offset with closing speed at 100 km/h. Hybrid Ⅲ 50th percentile male dummies were used to study the injury levels for the driver and passenger positions. See Figure 21.

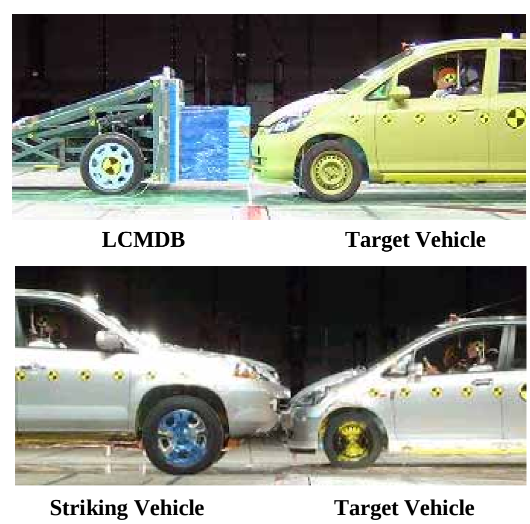


Figure 21. LCMDB-to-vehicle test configuration

Figure 22 shows the vehicle deformation and the dummy responses for the target vehicle. Fairly good fidelity was observed with regard to the vehicle deformation. Injury Assessment Reference Values (IARVs) was used to normalize the injury measurements. These reference values are defined in FMVSS 208. The result of the LCMDB-to-vehicle test shows that the injury measures were greater overall than those in the vehicle-to-vehicle test.

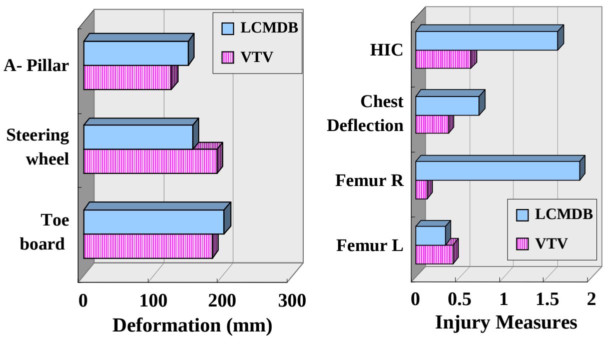


Figure 22. Comparison of vehicle deformation and injury measures for driver dummy

Barrier load cell data analysis

Figure 23 shows the contour graphs of the small vehicle which collided into the LCMDB in offset-frontal impact. From the contour graph, it was observed that the DB dispersed the crash forces over a wide area on the LCW. This is not an advantageous feature when considering load cell data analysis. Then, as can be seen in the contour graph at 30 ms, the load cells could not discriminate the stiff structure until the side member directly contacted the LCW. This could be a second issue of load cell data analysis with a deep DB.

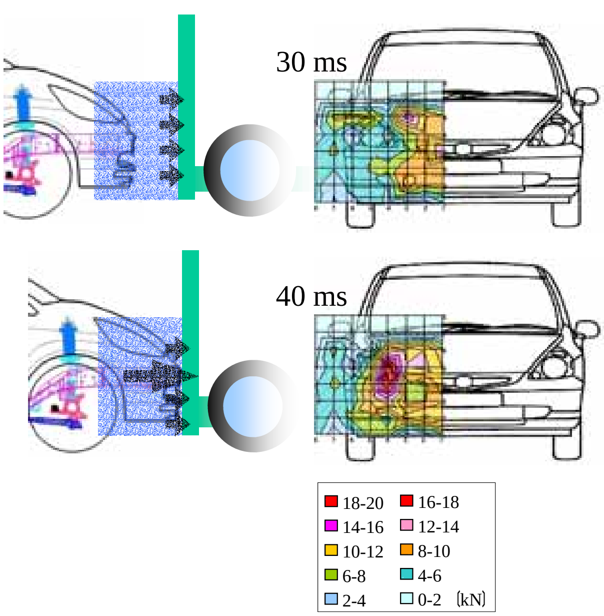


Figure 23. Load cell data analysis

Figure 24 compares the force-displacement characteristics of the target vehicle in the 64 km/h ODB test and in LCMDB test. The F-D curve in the LCMDB test was generally similar to those in the 64 km/h ODB test and obviously indicated an overload test for small vehicles. These F-D curves demonstrate that the LCMDB-to-vehicle test can simulate the ODB test and that the 80 km/h ODB test (over load test) can be replaced by the LCMDB test by choosing suitable test speeds.

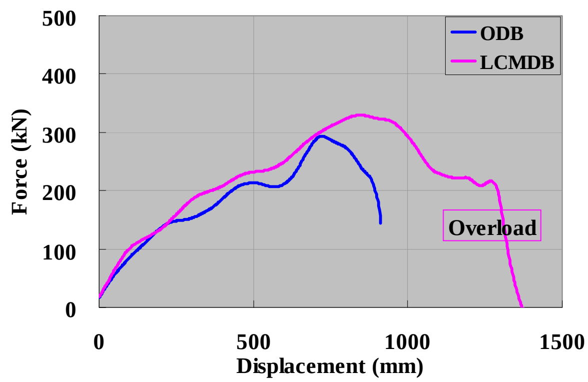


Figure 24. Comparison of force-displacement curves

Overall the load cell data analysis with deep DB may provide little information about what happens to the stiffness characteristics of the engine compartment. However, using an LCMDB test for assessing compartment strength can provide more realistic overload conditions, compared to the 80 km/h ODB test, on the basis that the LCMDB can represent large striking vehicles.

MDB-TO-VEHICLE OBLIQE-FRONTAL CRASH TESTS

Based on the analysis of National Automotive Sampling System (NASS) data, Ragland et al. reported that the frontal offset oblique crash test could be effective in enhancing vehicle safety performance in the real world [8, 9]. Enhancing the robustness of vehicle crashworthiness in relation to the impact angle may be quite important in real world accidents because almost all accidents have an impact angle, more or less. FMVSS 208 requires a fixed oblique barrier (FOB) test at 40km/h for occupant protection and FMVSS 301 requires the FOB test at 48km/h for fuel system integrity. However, fixed barrier tests only look at the crash condition between same weight vehicles. The MDB offers the ability to carry out various oblique offset tests. The MDB test method allows collisions of vehicles with different mass, which is unlikely to be confirmed by the fixed barrier test.

However, Sugimoto et al. reported the "bottoming out" issue of the DB in oblique-frontal MDB impact testing with an FMVSS 214 deformable face [10]. Therefore, an LCMDB with deeper DB was used to prevent bottoming out in this study, then vehicle and occupant kinematics were compared between the oblique-frontal LCMDB test and the vehicle-to-vehicle test.

A frontal 30 degrees oblique-frontal LCMDB-to-vehicle test was conducted according to the test configuration shown in Figure 25. At impact the left side corner of the target vehicle aligns with the center of the front of the striking LCMDB with a 100 km/h closing speed. A wider custom-build DB, which was twice as wide as that used in the offset-frontal test, was used for the oblique test. The load cell layout was the same as the full-frontal test (16 x 4). In this test, the target vehicle used a Hybrid III 50th percentile dummy which was restrained via seat belt in the driver position.

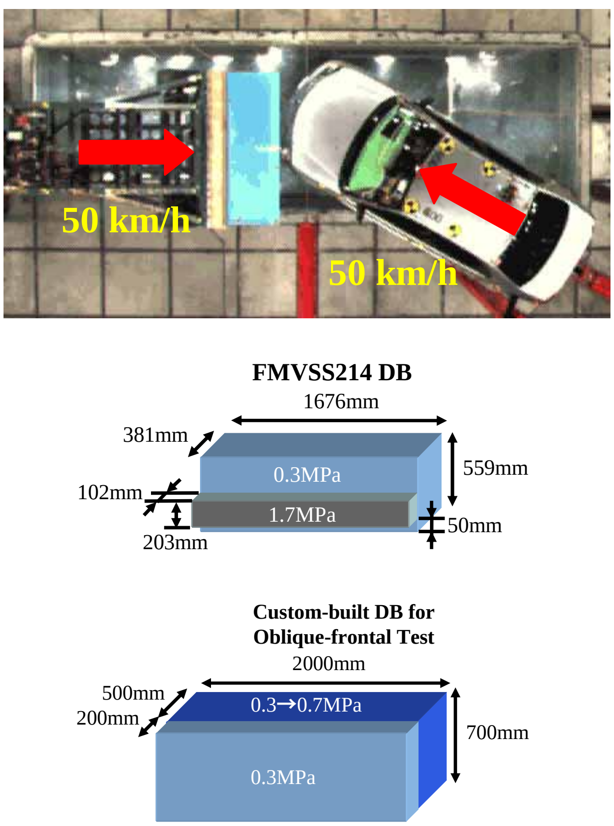


Figure 25. 30 degrees oblique-frontal LCMDB-to-vehicle test

The deformation levels and injury measures of the target vehicle were very similar for both the vehicle-to-vehicle (VTV) test and LCMDB-to-vehicle in comparison with the fixed oblique barrier test. See Figure 26.

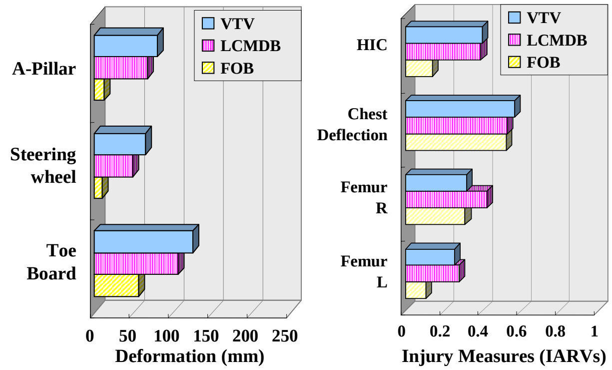


Figure 26. Comparison of vehicle deformations and injury measures for driver dummy

The primary difference in these data is seen in the time to rise from the initiation of the event. The vehicle deceleration in the LCMDB test begins to rise earlier than that in the vehicle-to-vehicle test. The deceleration pulse in the LCMDB test also shows a substantially shorter duration time. This may be caused by the lack of a bumper element for the LCMDB. See Figure 27.

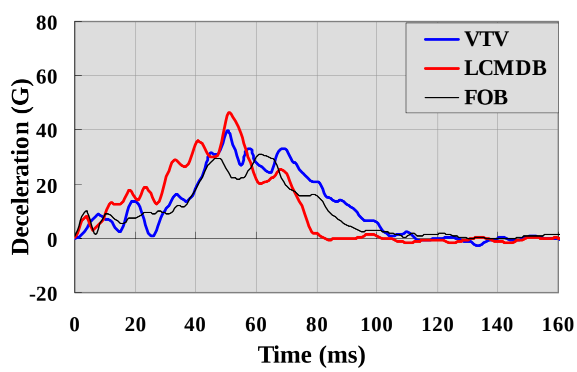


Figure 27. Comparison of vehicle deceleration pulses

The head responses of the dummy in the LCMDB test also rise earlier than in the vehicle-to-vehicle test, but are otherwise similar in terms of profile and magnitude. See Figure 28-30.

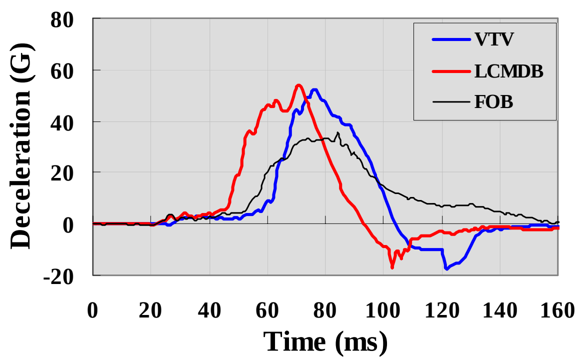


Figure 28. Comparison of Head-X deceleration pulses

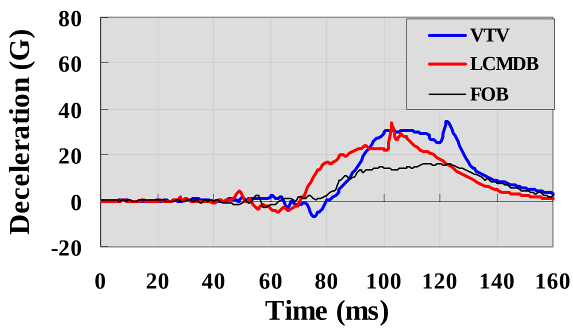


Figure 29. Comparison of Head-Y deceleration pulses

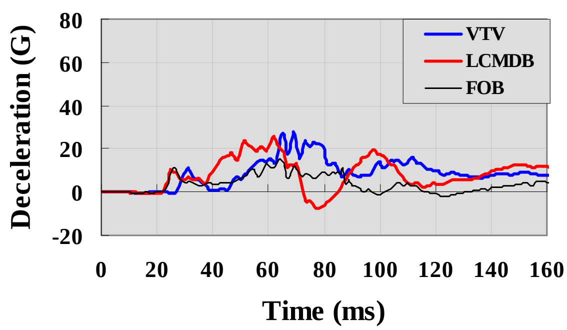


Figure 30. Comparison of Head-Z deceleration pulses

High speed video analysis was used to confirm kinematics of the events which are shown in Figure 31. The primary focus of this paper is on the vehicle dynamic response and occupant kinematics in the oblique-frontal LCMDB test configuration. As can be seen in Figure 31, the kinematics responses for these tests were very similar, both for the vehicle-to-vehicle test and the LCMDB-to-vehicle test respectably.

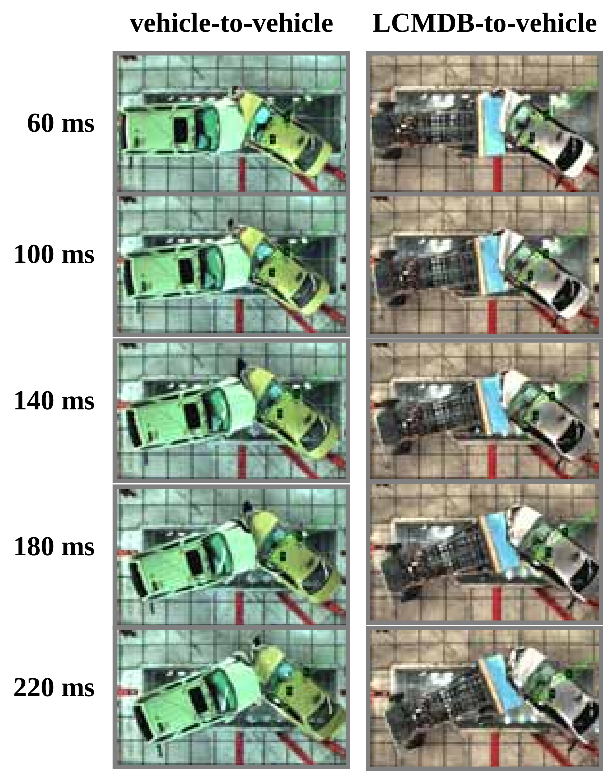


Figure 31. Comparison of vehicle kinematics responses

The dynamic movements of the right and left side A-pillar of the target vehicles were compared in figure 32. The trace in the LCMDB-to-vehicle test was similar to that in the vehicle-to-vehicle test, while the trace in the fixed oblique barrier (FOB) test was different from that of the vehicle-to-vehicle test in terms of the rebound movement of the target vehicle. This is because the LCMDB test can produce a mass effect in the vehicle dynamic responses.

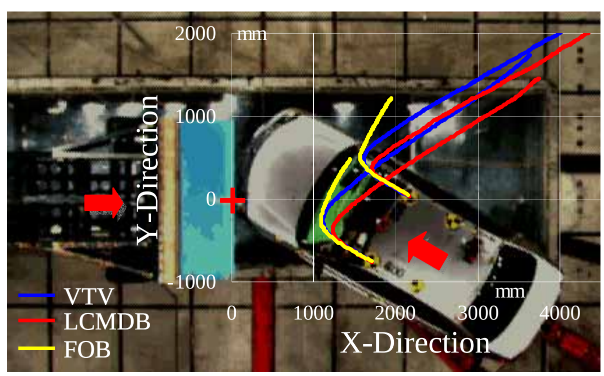


Figure 32. Comparison of A-Pillar traces (X, Y direction for LCMDB)

Since vehicle dynamic responses in the LCMDB test were similar to those in the vehicle-to-vehicle test, the driver dummy head kinematics in the LCMDB test was also similar to those in the vehicle-to-vehicle test. The rotational movement of the dummy head around the air bag was well simulated by the LCMDB testing. See Figure 33.

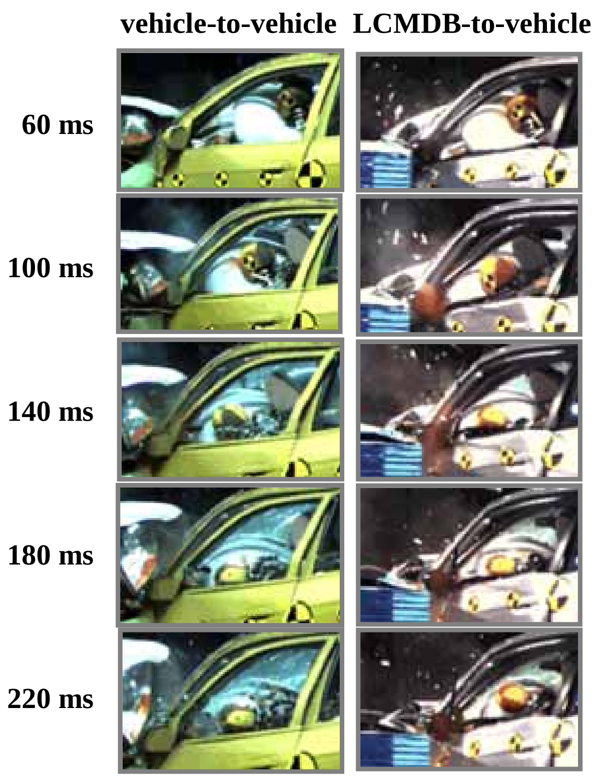


Figure 33. Comparison of dummy head kinematical responses

When comparing the F-D characteristics between the oblique-frontal LCMDB test and 64 km/h ODB test, the F-D curve in the oblique-frontal LCMDB test indicated over all a lower force level than that in the 64 km/h ODB test. The F-D curve in the early stages of the impact for the oblique-frontal LCMDB test indicated that energy absorption in the engine compartment of the target vehicle may be decreased by the oblique impact. Simultaneously total impact energy may also be decreased by the rotational movement of the vehicle. See Figure 34.

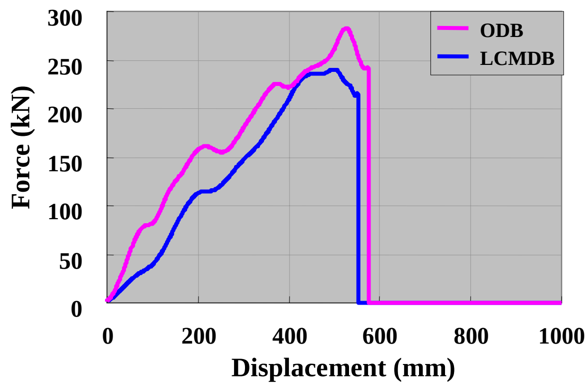


Figure 34. Comparison of force-displacement characteristics

Figure 35 shows the body deformation on the target vehicle in the LCMDB tests. The reason for the lower F-D curve in the LCMDB test may be because the oblique LCMDB impact applied lateral forces to the engine compartment and the side member of the target vehicle was unable to sufficiently to absorb the impact energy. It was observed for the target vehicle that the obviously lower deformation levels were seen at the front-end of the side member. An oblique offset LCMDB test may assess the robustness of impact energy absorption capability in engine compartments of vehicles against impact angle; hence the oblique offset LCMDB could be used to assess self-protection performance in the oblique impact.

Figure 35. Body deformation of the target vehicle

DISCUSSION

Testing of compatibility should evaluate the characteristics that can be changed to enhance compatibility in frontal impacts. According to a report published by the IHRA, structural interaction, frontal stiffness, passenger compartment strength, and deceleration pulse are important issues for frontal impact compatibility [11]. At present, vehicle fleets differ in mass, stiffness, geometry and many other design parameters in countries, and traffic environments also differ according to the country. The MDB test method is considered a research item for the longer term in the IHRA ; however, MDB-to-vehicle testing provides more flexibility in simulating vehicle-to-vehicle crashes, hence the MDB test would offer the best overall coverage of real world accidents.

CONCLUSION

This paper presented findings on LCMDB-to-vehicle crash testing for consideration in future research into frontal impact compatibility. In this study, the response characteristics of the target vehicles were compared to those in the fixed barrier and LCMDB crash test modes.

In full-frontal energy equivalent LCMDB tests with the shallow DB (2000 mm x 750 mm x 300 mm), while the peak LCW data values measured by the LCMDB test are slightly different from those measured by FWDB testing, the profiles of the data producing the results are comparable. The full-frontal LCMDB test could use the compatibility metrics of fixed barrier tests to assess the interaction characteristics and the stiffness of vehicles (sometimes referred to as the "aggressivity" of vehicles). Repeatability tests will be required for full-frontal LCMDB tests to confirm the stability of the compatibility metrics between tests.

In offset-frontal LCMDB tests with the custom-built DB (1000 mm x 700 mm x 700 mm), using heavy LCMDBs representing large striking vehicles may produce more realistic overload conditions, which simulate the body deformation and deceleration observed in actual vehicle-to-vehicle impacts, to evaluate the passenger compartment strength for small vehicles. Hence an LCMDB collinear offset impact could evaluate self-protection performance for small vehicles.

In oblique-frontal LCMDB tests with the custom-built DB (2000 mm x 700 mm x 700 mm), the results of the 30-degree oblique offset LCMDB test clearly show that the response characteristics of both the target vehicle and the occupant in the LCMDB-to-vehicle test are similar to those in the vehicle-to-vehicle test. Since an oblique-frontal LCMDB test may assess the energy absorption capability in the engine compartment of vehicles, the oblique-frontal LCMDB test may evaluate robustness of self-protection performance of vehicles against impact angles.

Overall, the LCMDB could be used as an advanced assessment device for use in frontal compatibility testing. Compared to fixed barrier tests, LCMDB testing has improved the fidelity of vehicle-to-vehicle impact in terms of the mass ratio to be taken into account. The LCMDB test method calls for further investigation, however, the LCMDB testing might have significant advantages in comparison with fixed barrier tests.

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Vehicle Aggressiveness in Real World Crashes

Rory Austin
National Highway Traffic Safety Administration
United States
Paper Number 05-0248

ABSTRACT

The National Highway Traffic Safety Administration (NHTSA) has identified vehicle compatibility as one of its five priorities. One important component of vehicle compatibility in head-on and side impact crashes is vehicle aggressiveness. Aggressivity of a vehicle is defined as the fatality or injury risk for occupants of other vehicles with which it collides. More aggressive vehicles are more likely to produce serious injuries to occupants of the vehicles with which they collide than less aggressive vehicles. NHTSA has studied the variation in vehicle aggressiveness for over twenty five years. One recent effort using police reported crashes to understand vehicle aggressiveness was contained in the technical report “Vehicle Weight, Fatality Risk, and Crash Compatibility” by Kahane. This paper aims to validate the compatibility findings of Kahane’s report by including additional years of crash data and by employing a different methodology.

Vehicle aggressiveness is determined using five years of police reported crashes from seven states in NHTSA’s State Data System (SDS). The injury status of drivers in head-on crashes between a light truck or van (LTV) and a passenger car and in nearside crashes where a passenger car was struck on the left (driver’s) side by another light duty vehicle are examined separately. The results demonstrate the relationship between a vehicle’s aggressiveness and its body style, mass, and other physical characteristics. The robustness of the results is tested using controls for driver and crash characteristics. For the most part, the results confirm the importance of physical characteristics for understanding vehicle aggresiveness measured from police reported crashes.

INTRODUCTION

In June 2003, NHTSA released the report, “Initiatives to Address Vehicle Compatibility” [1]. This report presented an in-depth examination of the safety problem represented by vehicle incompatibility and provided strategies to improve vehicle compatibility. In addition, the background section documented over twenty five years of NHTSA research to understand and control vehicle aggressiveness. The safety problem section addressed current concerns regarding the increased exposure of car occupants to collisions with LTVs, the large and growing fatalities in collisions involving a car and an LTV, and the greater fatality risk for the car driver than the LTV driver in these collisions.

The safety assessment conclusions were further confirmed in a NHTSA report, “Vehicle Weight, Fatality Risk and Crash Compatibility of Model Year 1991-99 Passenger Cars and Light Trucks,” released in October, 2003, by Charles Kahane [2]. According to Kahane’s report, LTVs were more aggressive to car drivers than other cars in head-on and nearside (left or driver’s side) crashes, even when controlling for differences in vehicle weight.

Kahane also evaluated two physical parameters of vehicles derived from NHTSA’s New Car Assessment Program (NCAP) frontal impact testing [3]. In nearside crashes involving an LTV and a car, Kahane found that the difference between the average height of force (AHOF) of the struck car and the striking LTV had a statistically significant negative effect on the car driver’s fatality risk. Thus the more negative the difference, due either to a lower AHOF for the struck car or a higher AHOF for the striking LTV, the greater the fatality risk for the car driver. In head-on crashes involving a car and an LTV, Kahane found that the frontal stiffness of the LTV had a statistically significant positive effect on the fatality risk for the car driver.

This present study is different from Kahane’s in many ways. In particular, this study predicts the probability of a serious injury or fatality given that a crash occurred rather than the fatality risk per billion miles. Instead of national fatality counts, this study focuses on police-reported crashes in seven states. Finally, the model years include vehicles from 1985 through 2002 although the analysis of physical characteristics includes mostly newer vehicles because of data availability. This study does not aim to replace or to update the "Vehicle Weight, Fatality Risk and Crash Compatibility" report but aims to serve as a complement that furthers our understanding of vehicle compatibility and aggressiveness.

DATA

This analysis uses police reported crashes from seven states in NHTSA's State Data System (SDS). The states were selected based upon the availability of vehicle identification numbers (VINs) and of initial impact points. The most recent five years of the SDS (1998 to 2002) were used in five of the states. Four years of Pennsylvania crashes were used because the 2002 file was not yet available. Three years of Kentucky crashes were used because the initial point of impact was added in 2000.

The analysis includes only light duty vehicles (vehicles with a Gross Vehicle Weight Rating of 10,000 pounds or less) as indicated by a valid VIN. Light duty vehicles include passenger cars, compact and standard pickups, utility vehicles, minivans, and large vans. Pickups, utility vehicles, and vans are also referred to as light trucks and vans or LTVs. For consistency with the VIN decoding programs decribed below, the analysis was restricted to vehicles of model year 1985 through 2003. Head-on impact crashes are defined as two vehicle crashes where the initial point of impact for both vehicles was the front (including front corners). Nearside impact crashes are defined as two vehicle crashes where the initial impact point was front for the striking vehicle and the left (driver's) side for the struck vehicle. Crashes involving a rollover or an overturned vehicle are excluded from the analysis.

Finally, the crashes of most interest in this analysis involve a car struck by a pickup, utility vehicle, or van, but the analysis includes cars struck by cars for comparative purposes. Head-on and nearside crashes involving two LTVs as well as nearside crashes where a car struck an LTV in the side are excluded. Table 1 lists the states and the years used in the analysis. The number of crashes across states differs in part because the states do not have a standard definition of impact points. These differences are controlled in later analysis by using state indicator variables.

The state files provided information about all of the drivers involved in the crash including injury severity, age, and gender. While the definition of injury severity differed across the states, this paper defines seriously injured drivers to include fatalities as well as survivors with injuries of the highest severity level noted on the police report (usually incapacititating injuries). Age is divided into four categories for analysis purposes: 14 to 29 years old, 30 to 49 years old, 50 to 69 years old, and 70 years old or older. These categories are the same as those used in the "Vehicle Weight, Fatality Risk and Crash Compatibility" report.

Table 1.
State Data System (SDS) files used in analysis

State	Years	Head-on Crashes	Nearside Crashes
LTV strikes Car			
Florida	1998-2002	22,818	15,054
Illinois	1998-2002	39,790	9,438
Kentucky	2000-2002	11,791	3,259
Maryland	1998-2002	7,845	4,305
Missouri	1998-2002	12,649	8,947
Pennsylvania	1998-2001	16,752	5,925
Wyoming	1998-2002	1,622	546
Car strikes Car			
Florida	1998-2002	28,512	45,692
Illinois	1998-2002	56,844	29,807
Kentucky	2000-2002	12,421	8,747
Maryland	1998-2002	11,010	14,173
Missouri	1998-2002	14,066	25,680
Pennsylvania	1998-2001	21,546	17,911
Wyoming	1998-2002	1,219	1,173
TOTAL		258,885	190,657

Two additional crash variables are derived from the state files. First, an indicator variable was created that identifies crashes where the speed limit was 50 miles per hour (mph) or higher. In Pennsylvania, the variable indicates whether any of the roads had a speed limit of 50 mph or higher. A second indicator variable identifies crashes where any of the drivers involved may have been impaired by alcohol or drugs.

One variable that is not used in this analysis is restraint or belt use. Belt use derived from police-reported crashes is believed to have large measurement error. The belt use in police-reported crashes in these states is larger than the estimates of belt use based upon observations from NHTSA's National Occupant Protection Use Survey (NOPUS). Furthermore, many of the states report more cases of unknown belt usage than cases of unbelted drivers. Finally, uninjured and less severely injured drivers may be more likely to overreport belt usage than more severely injured drivers. Given the large and potentially non-random measurement error in belt usage, it is not included in this analysis. However, many of the other explanatory variables (age, sex, crashes involving impaired drivers, and even state) may partially capture the effects of belt usage because they are correlated with restraint use [4].

NHTSA staff developed a series of programs to identify a vehicle's make, model, model year, LTV type, and air bag availability based upon the VIN. This analysis uses the latest version of these programs, which decode VINs of light duty vehicles from model year 1985 through 2003. The output from these programs was used to create an indicator for the presence of a driver-side front airbag, to calculate the age of the vehicle at the time of the crash, and to assign a vehicle type of car, compact pickup, standard pickup, minivan, full-size van, or utility vehicle.

These programs also assign a four-digit code that identifies a fundamental vehicle group. These groups contain all vehicles of the same type and wheelbase that run for several model years until they are redesigned. These vehicle groups are important for identifying when a vehicle parameter for one model year may be applied to other model years of the same make and model as well as across similar vehicles with different names (corporate twins).

This analysis also makes use of three vehicle parameters from NHTSA's compliance and crash tests to help explain the likelihood of a serious injury: curb weight, average height of force (AHOF), and front-end stiffness. The vehicle weights are from Federal Motor Vehicle Safety Standard (FMVSS) No. 208 and No. 301 compliance tests as well as U.S. New Car Assessment Program (NCAP) crash tests. The vehicle weights were supplemented by curb weights for model year 1991 through 1999 from the "Vehicle Weight, Fatality Risk, and Crash Compatibility" report. The additional curb weights, which predominatly came from manufacturers' reports, were adjusted to adjust for differences between reported and actual curb weights as described in Kahane's report [3, p. 19].

Average height of force and front-end stiffness are derived from frontal NCAP barrier testing. AHOF is the weighted average of the height of the applied force measured by load cells at various height levels. Front-end stiffness is the average slope of the force-deflection profile measured by the load cells. Table 2 contains some descriptive statistics for curb weight, AHOF, and stiffness.

Table 2.
Vehicle parameters by vehicle type

Vehicle Type	Curb Weight (pounds)	AHOF (mm)	Stiffness (Newtons per mm)
Car	3,072	442	1,124
Compact Pickup	3,316	511	2,299
Standard Pickup	4,927	528	2,244
Utility	3,985	531	2,200
Minivan	3,917	491	1,854
Full-size Van	5,057	551	2,628

METHODS

The unit of analysis in this study is the two vehicle crash. For nearside crashes, the dependent or prediction variable is whether the car driver, struck on the nearside by either another car or an LTV, experienced a serious injury (fatal or incapacitating). For head-on crashes, there is no clear struck or striking vehicle. In a head-on crash involving an LTV and a car, the dependent variable is whether the car driver experienced a serious injury. For head-on crashes involving two cars, one of the drivers was selected at random, and the dependent variable is whether the randomly chosen driver experienced a serious injury.

The decision to select one driver at random involves both disadvantages and advantages. The major disadvantage is that it discards the injury data for the other driver. The advantage is that it simplifies the statistical modeling. The injury information for both drivers in a head-on crash does not represent two independent observations but rather two outcomes from the same event. Therefore, the error structure of the prediction model would need to account for the expected correlation of unmeasured factors that are experienced by both drivers in the same crash. Choosing one driver eliminates the need to adopt a more complicated, and potentially less robust, statistical model. Additionally, the focus of this paper is LTV versus car crashes with the car to car crashes, of which there are a relatively large number, included only for comparison purposes.

The statistical method employed in this paper is logistic regression. Logistic regression parallels linear regression analysis where the dependent variable is a linear function of the explanatory or independent variables. However, the dependent variable in a logistic regression is the natural log of the ratio of the probability of an event occurring to the probability of the event not occurring, which is also called the log odds ratio. In this study, the dependent variable is the natural log of the ratio of the probability of the car driver experiencing a serious injury to the probability of the car driver **not** experiencing a serious injury.

The coefficients produced by the model estimation provide an estimate of the effect of a one unit change in the independent variable on the natural log of the odds ratio of experiencing a serious injury, which is not a conventional way of framing effects. However, the odds ratio can be found by taking Euler's constant (e) raised to the power of the coefficient, which is easier to interpret because it indicates how the odds of an event occurring change as you change the independent variable by one unit. If an odds ratio is less than one, it suggests that an increase in the independent variable decreases the odds of the event occurring by decreasing the probability of the event. If the odds ratio is greater than one, it suggests that an increase in the independent variable increases the odds of the event occurring by increasing the probability of the event. If the odds ratio is equal to one, it indicates that the independent variable has no effect on the likelihood of the event occurring because the probability of the event occurring did not change. Odds ratios for each independent variable are presented in the tables of results.

Logistic regression also enables tests of whether the effect of an explanatory variable on the likelihood of a serious injury is statistically significant (unlikely to have occurred by chance or randomness). The test statistic is Chi-square, and statistical significance (stat. sig.) is the probably of a Chi-square of a particular value occurring given the null hypothesis assumption that the independent variable has no effect. A sufficiently low probably, usually below 0.05, would lead us to reject the null hypothesis in favor of the alternative that the independent variable has some effect.

RESULTS

This section contains the results of logistic regression models that predict serious injury to car drivers. The results for head-on crashes are presented first, followed by the results for nearside crashes. For both types of crashes, the results begin with the most simple statistical model involving only the type of other vehicle and the state controls. The second model includes the type of other vehicle, the state variables, and driver and crash characteristics. The third model contains all of the variables in the second model plus the difference of logged vehicle weights to test whether the type of other vehicle remains a statistically significant factor. The fourth model is slightly different from the previous models because it only contains crashes involving a car and an LTV. The purpose of the fourth model is to explore vehicle parameters other than weight that may explain differences in the aggressiveness across LTV body types.

Head-on Crashes

The first logistic regression model predicts the likelihood of a serious injury to a car driver in a front to front crash with another car or an LTV. The independent variables include indicator variables for the body type of the other vehicle and for the state where the crash occurred. The results are presented in Table 3.

Cases where the other vehicle is a car were set as the base or comparison case so that the odds ratios reflect the difference in the risk of a serious injury from a crash involving an LTV relative to a car. In all cases, the car driver in a head-on crash has a statistically significant higher risk of a serious injury when the other vehicle is an LTV compared to a car. The increased risk ranges from a 30 percent higher risk when the other vehicle is a minivan to almost twice as large a risk when the other vehicle is a standard pickup. Florida was selected as the base case for the states, and the fact that most of the state variables indicate a significantly different risk confirms the importance of including state identifiers.

Table 3.
Logistic regression of serious injuries to car drivers in head-on crash by other vehicle type

Variable	Coef-ficient	Chi-Square	Stat. Sig.	Odds Ratio
Intercept	-2.822	19013	0.001	
Car	0.000			1.00
Compact Pickup	0.461	192.32	0.001	1.59
Standard Pickup	0.677	475.91	0.001	1.97
Utility Vehicle	0.335	138.08	0.001	1.40
Minivan	0.263	58.67	0.001	1.30
Full-size Van	0.434	71.08	0.001	1.54
Florida	0.000			1.00
Illinois	-0.792	966.25	0.001	0.45
Kentucky	-0.591	253.26	0.001	0.55
Maryland	-0.038	1.23	0.267	0.96
Missouri	-0.505	210.91	0.001	0.60
Pennsylvania	-1.076	820.18	0.001	0.34
Wyoming	-0.741	53.51	0.001	0.48

Note: N = 258,885; Seriously Injured = 10,956

While the above estimates provide a starting point for understanding compatibility, they do not control for other driver and crash characteristics that may explain the differences across vehicle types. The next logistic regression contains several explanatory variables in addition to the vehicle type and state indicators. The statistical model includes age categories separately for males and females. The age-gender categories of both the case vehicle and the other vehicle are likely to capture some aspects of crash severity. The age-gender categories for the case vehicle also reflect the effect of these variables on the likelihood of experiencing a severe injury [5]. Additional explanatory variables include indicators for the presence of a front driver's side airbag, for whether any of the drivers were impaired by alcohol or drugs, and whether the speed limit was 50 mph or higher. The age of the case vehicle was originally included in the model of head-on crashes, but it was dropped because its effect never achieved statistical significance. The complete results are contained in Table 4.

All of the control variables achieved statistical significance in the expected direction in the logistic regression of serious injuries to car drivers in head-on crashes by vehicle type and driver and crash characteristics. The risk of serious injury to the car driver was more than three times greater when the speed limit was 50 mph or greater and when the crash involved one or more impaired drivers. The presence of an airbag in the case car decreased the probability of a serious injury. A female driver was more likely to experience a serious injury than a male driver at all age levels, and older drivers of both genders were more likely to experience a serious injury than younger drivers. In fact, car drivers in the oldest age group (70 years old and older) were about twice as likely to experience a serious injury than the youngest age group (14 to 29 years old). The signs on the age-gender categories of the other driver were all negative and were usually statistically significant. The negative sign indicates a lower probability of a serious injury compared to the other driver being a male aged 14 to 29. This result may reflect some aspect of crash severity due to the driving behavior of the youngest males.

Even when controlling for these driver and crash characteristics, the car driver in a head-on crash still has a statistically significant higher risk of a serious injury when the other vehicle is an LTV compared to a car. The increased risk ranges from about a 30 percent higher risk when the other vehicle is a minivan to 60 percent higher when the other vehicle is a standard pickup. The lower range of risk than in the previous model is due to the explanatory power of the additional control variables.

Table 4.
Logistic regression of serious injuries to car drivers in head-on crash by other vehicle type and driver and crash characteristics

Variable	Coef-ficient	Chi-Square	Stat. Sig.	Odds Ratio
Intercept	-3.088	7040.8	0.001	
Car	0.000			1.00
Compact Pickup	0.298	73.9	0.001	1.35
Standard Pickup	0.470	202.2	0.001	1.60
Utility Vehicle	0.325	123.4	0.001	1.38
Minivan	0.273	59.7	0.001	1.31
Full-size Van	0.396	55.9	0.001	1.49
Speed limit 50 or over	1.198	2555.4	0.001	3.31
Impaired crash	1.228	1667.8	0.001	3.42
Airbag	-0.295	212.4	0.001	0.74
This driver				
Male 14-29	0.000			1.00
Male 30-49	0.118	10.9	0.001	1.13
Male 50-69	0.221	24.9	0.001	1.25
Male 70+	0.534	109.6	0.001	1.71
Female 14-29	0.264	66.9	0.001	1.30
Female 30-49	0.459	187.2	0.001	1.58
Female 50-69	0.518	164.9	0.001	1.68
Female 70+	0.756	243.3	0.001	2.13
Other driver				
Male 14-29	0.000			1.00
Male 30-49	-0.078	6.9	0.008	0.93
Male 50-69	-0.077	4.4	0.036	0.93
Male 70+	-0.077	1.8	0.175	0.93
Female 14-29	-0.174	24.6	0.001	0.84
Female 30-49	-0.185	29.7	0.001	0.83
Female 50-69	-0.085	3.5	0.063	0.92
Female 70+	-0.082	1.3	0.254	0.92
Florida	0.000			1.00
Illinois	-0.729	784.3	0.001	0.48
Kentucky	-0.767	399.7	0.001	0.46
Maryland	-0.070	3.9	0.047	0.93
Missouri	-0.609	288.8	0.001	0.54
Pennsylvania	-1.214	1007.2	0.001	0.30
Wyoming	-0.712	48.3	0.001	0.49

Note: N = 258,885; Seriously Injured = 10,956

One explanation for the higher risk of serious injury for a car driver in head-on crashes with an LTV than another car is the difference in the vehicles' masses. To test this proposition, the difference between the logged curb weight of the case vehicle and logged curb weight of the other vehicle was added to the model. (This difference is also the log of the curb weight ratio.) The natural log transformation, which was used in Kahane's study, creates a more linear relationship between weight and injury risk. The complete results are contained in Table 5.

Table 5.
Logistic regression of serious injuries to car drivers in head-on crash by other vehicle type, crash characteristics, and weight difference

Variable	Coef-ficient	Chi-Square	Stat. Sig.	Odds Ratio
Intercept	-3.102	5710.16	0.001	
Difference in logged weight	-0.842	310.46	0.001	0.43
Car	0.000			1.00
Pickup	0.171	29.28	0.001	1.19
Utility Vehicle	0.090	6.84	0.009	1.09
Minivan	0.080	3.78	0.052	1.08
Full-size Van	-0.058	0.60	0.440	0.94
Speed limit 50 or over	1.201	2112.24	0.001	3.32
Impaired crash	1.222	1310.69	0.001	3.39
Airbag	-0.274	146.06	0.001	0.76
This driver				
Male 14-29	0.000			1.00
Male 30-49	0.137	11.62	0.001	1.15
Male 50-69	0.312	40.43	0.001	1.37
Male 70+	0.604	111.35	0.001	1.83
Female 14-29	0.218	37.29	0.001	1.24
Female 30-49	0.472	162.22	0.001	1.60
Female 50-69	0.560	159.18	0.001	1.75
Female 70+	0.825	237.83	0.001	2.28
Other driver				
Male 14-29	0.000			1.00
Male 30-49	-0.120	13.65	0.000	0.89
Male 50-69	-0.143	12.24	0.001	0.87
Male 70+	-0.152	5.89	0.015	0.86
Female 14-29	-0.182	22.25	0.001	0.83
Female 30-49	-0.217	33.67	0.001	0.81
Female 50-69	-0.134	7.13	0.008	0.88
Female 70+	-0.114	2.14	0.143	0.89
Florida	0.000			1.00
Illinois	-0.732	659.55	0.001	0.48
Kentucky	-0.756	327.00	0.001	0.47
Maryland	-0.056	2.08	0.149	0.95
Missouri	-0.639	256.39	0.001	0.53
Pennsylvania	-1.251	834.66	0.001	0.29
Wyoming	-0.776	45.14	0.001	0.46

Note: N= 218,649, Seriously Injured = 9,041

The difference in curb weight has the expected strong effect. After controlling for the differences in curb weight, car drivers in a head-on crash still have a statistically significant greater risk of a serious injury when the other vehicle is a pickup or a utility vehicle than another car. The risk is also greater when the other vehicle is a minivan, but it is significant at the 0.10 level rather than the conventional 0.05 level. The difference in risk when the other vehicle is a full-size van compared to a car disappears with the addition of the curb weight variable.

The last model of the risk of serious injury to a car driver in a head-on crash includes only crashes involving a car and an LTV. The LTV body type variables are replaced with two physical LTV characteristics. One is the frontal stiffness of the LTV. The other is the difference between the average height of force of the car and the LTV. The sample size drops considerably compared to the previous models, but it remains large enough for meaningful analysis. This statistical model focuses exclusively on car-LTV head-on collisions because these variables have been shown to have different effects in car-LTV crashes than in car-car crashes. Also, full-size vans are excluded to make the results more comparable to those reported in "Vehicle Weight, Fatality Risk and Crash Compatibility." The results therefore help explain why some LTVs, particularly pickups, present a higher fatality risk to a car driver in head-on crashes than other LTVs, such as minivans, even when controlling for differences in vehicle weight. Table 6 contains the complete set of results.

Consistent with Kahane's results, LTV stiffness has a positive effect on the probability of a serious injury for the car driver in a head-on crash. The result, though, is statistically significant at the 0.10 level but not the conventional 0.05 level. The odds ratio for LTV stiffness may appear too small to indicate any explanation of LTV aggressiveness, but by definition the odds ratio indicates the change in the odds from a one unit, in this case one Newton per millimeter, increase in stiffness. If stiffness were increased 200 Newtons per mm, about 10 percent for most LTVs, the odd ratio increases to 1.01 or about a 1 percent higher risk of a serious or fatal injury. The difference in the average height of force did not have a statistically significant effect.

Table 6.
Logistic regression of serious injuries to car drivers in head-on crash with pickup, utility vehicle, or minivan by LTV characteristics

Variable	Coef-ficient	Chi-Square	Stat. Sig.	Odds Ratio
Intercept	-3.023	583.51	0.001	
Difference in logged weight	-0.682	26.94	0.001	0.51
LTV stiffness	0.000055	2.71	0.100	1.0001
Difference in AHOF	-0.000300	0.47	0.491	1.00
Speed limit 50 or over	1.133	353.87	0.001	3.11
Impaired crash	1.257	272.51	0.001	3.52
Airbag	-0.223	17.14	0.001	0.80
This driver				
Male 14-29	0.000			1.00
Male 30-49	0.069	0.57	0.450	1.07
Male 50-69	0.156	1.75	0.187	1.17
Male 70+	0.376	7.19	0.007	1.46
Female 14-29	0.160	3.61	0.057	1.17
Female 30-49	0.484	33.01	0.001	1.62
Female 50-69	0.439	17.70	0.001	1.55
Female 70+	0.719	32.61	0.001	2.05
Other driver				
Male 14-29	0.000			1.00
Male 30-49	-0.202	8.12	0.004	0.82
Male 50-69	-0.295	10.62	0.001	0.75
Male 70+	0.038	0.08	0.783	1.04
Female 14-29	-0.254	5.99	0.014	0.78
Female 30-49	-0.235	7.87	0.005	0.79
Female 50-69	-0.184	1.90	0.168	0.83
Female 70+	-0.379	1.06	0.303	0.68
Florida	0.000			1.00
Illinois	-0.731	105.09	0.001	0.48
Kentucky	-0.722	59.82	0.001	0.49
Maryland	0.040	0.19	0.664	1.04
Missouri	-0.635	46.13	0.001	0.53
Pennsylvania	-1.115	126.00	0.001	0.33
Wyoming	-0.495	3.89	0.048	0.61

Note: N = 32,640, Seriously Injured = 1,615

Nearside Crashes

Statistical models similar to those used to predict serious injuries to a car driver in head-on crashes were also applied to estimating the probability of a serious injury for a car driver struck on the left side (nearside) by the front of another vehicle. The first model contains the type of striking vehicle and the state indicators. Once again the car is the base or comparison striking vehicle type. The results are contained in Table 7.

Table 7.
Logistic regression of serious injuries to car drivers in nearside crash by other vehicle type

Variable	Coef-ficient	Chi-Square	Stat. Sig.	Odds Ratio
Intercept	-2.784	24215	0.001	
Car	0.000			1.00
Compact Pickup	0.670	244.86	0.001	1.96
Standard Pickup	1.020	780.95	0.001	2.77
Utility Vehicle	0.712	411.50	0.001	2.04
Minivan	0.378	62.17	0.001	1.46
Full-size Van	0.748	163.86	0.001	2.11
Florida	0.000			1.00
Illinois	-0.758	565.31	0.001	0.47
Kentucky	-0.723	203.30	0.001	0.49
Maryland	-0.046	1.93	0.164	0.96
Missouri	-1.001	768.19	0.001	0.37
Pennsylvania	-1.095	614.42	0.001	0.34
Wyoming	-1.118	56.06	0.001	0.33

N = 190,657, Seriously Injured = 9,059

In all cases, the car driver in a nearside crash has a statistically significant higher risk of a serious injury when the striking vehicle is an LTV compared to a car. The increased risk ranges from about a 50 percent higher risk when the other vehicle is a minivan to almost three times as large a risk when the other vehicle is a standard pickup.

The next statistical model includes the various driver and crash characteristics. There is only a small change from the model of the likelihood of serious injury in head-on crashes to the model in nearside crashes. The airbag variable, which indicated a front airbag for the driver, is dropped, but the presence of side impact airbags is not readily available. Instead, the age of the struck vehicle is added to the models. This variable, which was not included in the head-on models because it never achieved statistical significance, does achieve statistical significance in the nearside models. Otherwise, the explanatory variables are the same as those described previously. The complete results for the logistic regression model of serious injuries to car drivers struck on the nearside by vehicle type and driver and crash characteristics are included in Table 8.

Table 8.
Logistic regression of serious injuries to car drivers in nearside crash by other vehicle type and driver and crash characteristics

Variable	Coef-ficient	Chi-Square	Stat. Sig.	Odds Ratio
Intercept	-3.327	5935.27	0.001	
Car	0.000			1.00
Compact Pickup	0.530	143.90	0.001	1.70
Standard Pickup	0.862	500.68	0.001	2.37
Utility Vehicle	0.681	361.91	0.001	1.98
Minivan	0.366	55.80	0.001	1.44
Full-size Van	0.706	139.07	0.001	2.03
Speed limit 50 or over	0.929	1149.44	0.001	2.53
Impaired crash	0.801	403.95	0.001	2.23
Vehicle age	0.027	101.81	0.001	1.03
This driver				
Male 14-29	0.000			1.00
Male 30-49	0.041	0.97	0.325	1.04
Male 50-69	0.202	17.46	0.001	1.22
Male 70+	0.907	350.12	0.001	2.48
Female 14-29	0.375	96.04	0.001	1.46
Female 30-49	0.451	136.32	0.001	1.57
Female 50-69	0.690	244.10	0.001	1.99
Female 70+	1.048	439.58	0.001	2.85
Other driver				
Male 14-29	0.000			1.00
Male 30-49	-0.130	16.42	0.001	0.88
Male 50-69	-0.204	24.10	0.001	0.82
Male 70+	-0.289	22.98	0.001	0.75
Female 14-29	-0.239	43.54	0.001	0.79
Female 30-49	-0.196	29.02	0.001	0.82
Female 50-69	-0.291	33.63	0.001	0.75
Female 70+	-0.266	15.28	0.001	0.77
Florida	0.000			1.00
Illinois	-0.737	521.29	0.001	0.48
Kentucky	-0.858	277.14	0.001	0.42
Maryland	-0.091	7.15	0.008	0.91
Missouri	-1.094	881.74	0.001	0.34
Pennsylvania	-1.222	747.15	0.001	0.30
Wyoming	-1.112	54.96	0.001	0.33

Note: N = 190,657, Seriously Injured = 9,059

Table 8 indicates that the age-gender categories, the impaired crash indicator, and the speed limit of 50 mph or higher all have the expected statistically significant effects. Vehicle age also has a statistically significant effect such that the struck driver in an older vehicle has a higher risk of serious injury than a struck driver in a newer vehicle. Even with these additional control variables, the struck car driver still has a statistically significant higher risk of a serious injury when the other vehicle is an LTV compared to a car. The increased risk ranges from about 44 percent higher risk when the other vehicle is a minivan to over twice the risk when the other vehicle is a standard pickup than a car. The control variables do not appear to diminish the estimated aggressiveness of LTVs in nearside impacts as much as it was diminished in head-on crashes.

The third statistical model of the risk of serious injury to car drivers struck on the nearside adds the difference in the logged curb weights. The complete results of the model are contained in Table 9. The difference in curb weight has a strong effect on the probability of the struck driver experiencing a serious injury. Once the control for the difference in the weights is included, both striking minivans and full-size vans are no longer statistically different from striking cars in terms of the risk of serious injury experienced by the nearside struck car driver. However, car drivers struck on the nearside still have a statistically significant greater risk of a serious injury when the other vehicle is a pickup or a utility vehicle than a car.

The final model contains just car drivers struck on the nearside by pickups, utility vehicles, and minivans for the reasons discussed in the head-on crash section. The complete results are in Table 10 and are again consistent with the findings in Kahane's report. While the striking vehicle's stiffness did not have a statistically significant effect on the probability of serious injury for the struck car driver, the striking vehicle's average height of force did have a statistically significant effect. The odds ratio for AHOF may appear too small to indicate any explanation of LTV aggressiveness, but by definition the odds ratio indicates the change in the odds from a one unit, in this case one millimeter, increase in AHOF. An increase in the average height of force of 50 mm, about 10 percent for most LTVs, increases the risk of serious injury by about 7 percent. This relationship may be even stronger if the statistical model accounted for characteristics of the side of the struck vehicle such as side sill height, but it is still a strong predictor even without this additional information.

Table 9.
Logistic regression of serious injuries to car drivers in nearside crash by other vehicle type, crash characteristics, and weight difference

Variable	Coef-ficient	Chi-Square	Stat. Sig.	Odds Ratio
Intercept	-3.237	4714.84	0.001	
Difference in logged weight	-1.059	478.96	0.001	0.35
Car	0.000			1.00
Pickup	0.390	112.14	0.001	1.48
Utility Vehicle	0.337	65.66	0.001	1.40
Minivan	0.047	0.69	0.405	1.05
Full-size Van	0.112	1.94	0.163	1.12
Speed limit 50 or over	0.965	1047.25	0.001	2.63
Impaired crash	0.838	361.61	0.001	2.31
Vehicle age	0.026	71.78	0.001	1.03
This driver				
Male 14-29	0.000			1.00
Male 30-49	0.104	5.24	0.022	1.11
Male 50-69	0.319	36.12	0.001	1.38
Male 70+	0.999	349.00	0.001	2.71
Female 14-29	0.302	51.82	0.001	1.35
Female 30-49	0.453	114.67	0.001	1.57
Female 50-69	0.734	233.38	0.001	2.08
Female 70+	1.110	411.82	0.001	3.03
Other driver				
Male 14-29	0.000			1.00
Male 30-49	-0.202	32.77	0.001	0.82
Male 50-69	-0.281	37.88	0.001	0.76
Male 70+	-0.419	40.09	0.001	0.66
Female 14-29	-0.217	30.42	0.001	0.81
Female 30-49	-0.257	41.38	0.001	0.77
Female 50-69	-0.352	42.02	0.001	0.70
Female 70+	-0.317	19.03	0.001	0.73
Florida	0.000			1.00
Illinois	-0.770	479.26	0.001	0.46
Kentucky	-0.864	240.96	0.001	0.42
Maryland	-0.136	13.32	0.001	0.87
Missouri	-1.110	756.01	0.001	0.33
Pennsylvania	-1.247	626.41	0.001	0.29
Wyoming	-1.151	46.22	0.001	0.32

Note: N = 159,477, Seriously Injured = 7,623

Table 10.
Logistic regression of serious injuries to car drivers in nearside crash with pickup, utility vehicle, or minivan by LTV characteristics

Variable	Coef-ficient	Chi-Square	Stat. Sig.	Odds Ratio
Intercept	-3.646	120.07	0.001	
Difference in logged weight	-0.911	46.53	0.001	0.40
Striking LTV stiffness	0.00003	0.82	0.365	1.000
Striking LTV AHOF	0.00133	4.75	0.029	1.001
Speed limit 50 or over	1.044	224.06	0.001	2.84
Impaired crash	0.983	91.90	0.001	2.67
Vehicle age	0.023	9.23	0.002	1.02
This driver				
Male 14-29	0.000			1.00
Male 30-49	0.067	0.35	0.556	1.07
Male 50-69	0.471	13.43	0.000	1.60
Male 70+	1.112	74.63	0.001	3.04
Female 14-29	0.272	7.32	0.007	1.31
Female 30-49	0.322	9.38	0.002	1.38
Female 50-69	0.545	21.07	0.001	1.72
Female 70+	1.007	61.08	0.001	2.74
Other driver				
Male 14-29	0.000			1.00
Male 30-49	-0.191	6.01	0.014	0.83
Male 50-69	-0.304	9.03	0.003	0.74
Male 70+	-0.278	2.56	0.110	0.76
Female 14-29	-0.380	9.62	0.002	0.68
Female 30-49	-0.163	2.98	0.084	0.85
Female 50-69	-0.232	2.26	0.133	0.79
Female 70+	-0.547	1.88	0.170	0.58
Florida	0.000			1.00
Illinois	-0.810	83.39	0.001	0.45
Kentucky	-0.721	36.36	0.001	0.49
Maryland	-0.248	6.83	0.009	0.78
Missouri	-0.999	115.76	0.001	0.37
Pennsylvania	-1.134	102.86	0.001	0.32
Wyoming	-1.623	10.03	0.002	0.20

Note: N = 18,105, Seriously injured = 1,316

CONCLUSIONS

The findings in this paper are consistent with many of NHTSA's previous studies regarding vehicle compatibility and aggressiveness in head-on and nearside crashes [2, 3, 6, 7, 8] even though the methodology is quite different. The risk of a serious injury to a car driver struck head-on or struck on the nearside by an LTV is higher than when struck by another car even when controlling for driver and crash characteristics. Aggressiveness differs across LTVs with minivans at the lower end, utility vehicles in the middle, and standard pickups at the high end. These results are similar but do not exactly correspond to previous agency research. For example, the order from least to most aggressive LTV type in head-on crashes from "NHTSA's Research Program for Vehicle Compatibility" was compact pickup, minivan, small utility, large utility, large van, and large pickup [6, p. 2]. For side impact crashes, the order from least to most aggressive was minivan, compact pickup, small utility, large van, large pickup, and large utility [6, p. 3]. In this present study, the compact pickups tended to look more similar to utility vehicles than minivans in terms of aggressiveness.

When taking differences in curb weight into account, the aggressiveness of minivans and full-size vans disappears in nearside crashes and almost disappears in head-on crashes. This finding is similar to results presented in Kahane's study, which found that the higher aggressiveness of minivans compared to cars was no longer statistically significant when controlling for differences in vehicle weight. However, Kahane found that utility vehicles were more aggressive than pickups after controlling for weight while this study generally indicates that pickups were the most aggressive LTV category [2, pp.254-55].

For pickups and utility vehicles, curb weight alone does not explain the higher risk of serious injury to car drivers struck head-on or on the nearside. Among pickups, utility vehicles, and minivans, the average height of force explains why some of these vehicles are related to a higher risk of serious injury for a car driver struck on the nearside, and the stiffness of the LTV explains why some of these vehicles are related to higher risk of serious injury for a car driver struck head-on. These findings are consistent with the results presented in Kahane's report even though they are not exactly the same. In head-on crashes between an LTV and a car, Kahane found that the natural log of the LTV stiffness was a statistically significant predictor of the car driver's fatality risk. In nearside crashes where the front of an

LTV struck the left side of a car, Kahane found that the difference in the average height of force of the two vehicles was a statistically significant predictor of car driver's fatality risk [6, p.268]. This paper indicates similar results with the exception that the LTV stiffness itself, rather than the natural log of stiffness, was statistically significant. This paper also uses the LTV's AHOF in the nearside impact models rather than the difference in AHOF because of questions raised (and noted in Kahane's report) about the use of the car's AHOF as a surrogate for sill height.

Although these results do reinforce many of Kahane's findings, the results from a paper by Stephen Summers and Aloke Prasad prepared for the 19th Technical Conference on the Enhanced Safety of Vehicles (ESV) do not validate the findings in the laboratory. Summers and Prasad describe the results from three sets of vehicle-to-vehicle crash tests (full frontal, frontal 50% offset, and side impact) involving an LTV striking a car. According to their paper, "none of the three test series provided significant insight or understanding to explain the fleet correlations with stiffness and AHOF metrics" [9, p. 14].

Summers and Prasad suggest a couple of reasons why the results from statistical studies using police reported crashes, such as this paper and Kahane's study, may not be supported by laboratory crash tests. One reason may be that the crash severity in the laboratory tests may not be representative of the crash severity necessary for compatibility to play a significant role in the fleet data. It may be the case that aggressiveness is more apparent in high delta-V crashes, which are also the crashes that are most likely to produce serious injuries and fatalities, than in lower delta-V crashes. Another reason may be that the laboratory testing used a model year 2004 car while the statistical studies use historical data that includes vehicles as old as model year 1985. Therefore, statistical studies such as this one may not capture the most recent changes in vehicle design. In particular, changes in restraint systems, such as the addition of side curtain air bags, may help explain why the most current laboratory testing do not explain the fleet differences. Another reason not mentioned in the Summers and Prasad paper may be that the laboratory testing involved only one car model. It may be the case that LTV aggresiveness is more of an issue for some cars than for others.

Even in the crash data, the relationships between vehicle metrics and aggressiveness appear to be only part of the explanation. One reason is that the statistical noise in real world crashes may never be perfectly captured by explanatory variables. At the same time, increased attention to the accurate measurement and perhaps refinement of the physical characteristics of the vehicles, as well as the exploration of additional parameters, may increase our understanding of vehicle aggressiveness. Finally, future statistical studies should, as much as possible, explore the role played by vehicle design changes and improvements in restraint systems in predicting vehicle aggressiveness.

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AN ANALYSIS OF SPORT UTILITY VEHICLES INVOLVED IN ROAD ACCIDENTS

Dimitri Margaritis, Boudewijn Hoogvelt, Ydo de Vries, Cees Klootwijk, Herman Mooi
TNO Automotive
The Netherlands
Paper Number 05-0370

ABSTRACT

Trends are noticeable that the European car fleet is changing rapidly towards a higher diversity of vehicles on the roads. On the high end of the scale larger and heavier automobiles, such as Multi Purpose Vehicles (MPV's) and Sports Utility Vehicles (SUV's) take a larger share than before.

This paper shows the results from a study done on SUV accidents. The crash involvement and behaviour of Sports Utility Vehicles (SUV) was analysed. The analyses were based on a review of Dutch national statistics and in-depth studies of SUV accidents in The Netherlands and of passenger cars in Europe (the EACS project). Also comparisons were made with actual numbers of the car fleet of the vehicles types, so that exposure rates can be included. Accidents of vehicles in the above-described categories will also be compared with each other.

The national statistics and the in-depth analysis were compared and it was shown that the studies point in the same direction. It can be concluded that SUV's are significantly more aggressive against vulnerable road users. In this study no difference is found between heavy passenger cars and SUVs. SUVs are about as heavy as the average full-size passenger car. So the same mass difference occurs between passenger car classes (e.g. full-size and small cars). Although the bumper height is about 20% higher compared to passenger cars, this difference could not directly be related to an increase in injury severity in this study due to the lack of data.

INTRODUCTION

The Dutch car fleet is changing rapidly towards more extreme vehicles on the public roads. Larger and heavier vehicles, such as Sport Utility Vehicles (SUVs) are taking a larger share than before. The SUV sales in The Netherlands show a clear increase in the last five years. The success of these vehicles probably results from a public feeling on good ride and comfort, a safe feeling with respect to crashworthiness (self-protection) driving these cars and the fact that it is 'trendy' to own such a car.

At the moment many discussions are going on about the traffic safety aspect of SUV's, mainly about their aggressiveness. Some of their properties as size (geometry) and mass differ considerably from normal passenger cars. There is a lack of so called 'compatibility'. The worst item concerning compatibility is the height and especially the 'bumper height'. Other road-users feel threatened by SUV's because of the above mentioned differences. Accident studies for vehicle compatibility and traffic fatalities by vehicle type in the US show ([1], [2], [3], [4], and [5]) that the chance to get killed in a crash with a SUV, being an occupant in a passenger car is higher especially if the SUV is coming from the side. Another safety aspect is their rollover sensitivity. Research in this field show that SUVs tend to be more involved in vehicle rollover ([6], [7]). Normally, a passenger car never rolls over.

For this study the definition of an SUV is set to: *An SUV is a vehicle with a nose type front-end, a bigger geometry and an increased mass, front and rear bumper height, overall ground clearance and higher centre of gravity, in comparison to normal passenger cars. Terrain (off-road) vehicles and so called 'pickup-trucks' are also included in this definition.*

Firstly the methods used for the analysis of the data are described. Next the results are presented, subdivided into national traffic accident statistics and TNO in-depth database. Finally the conclusions and the recommendations are presented.

METHODS

A database with all SUV and passenger car accidents is built from the combination of the Dutch National Traffic Accident Statistics or in the Dutch 'Verkeers-Ongevallen-Registratie' (VOR) database of 2001 until August, 2002 and the Dutch licence plate registration system (RDW-data) to identify the vehicle types in a collision. All passenger car accidents and SUV accidents were extracted from the database. Normally all SUVs should be coded as passenger cars, however in the VOR in some cases these vehicles are also coded as ‘Van’ or ‘Truck’; this is taken into account in the selection. The names of SUV type vehicles were selected from several internet sources and year book lists. In total approximately 120 SUV types were identified. The collision partners of the selected vehicles were found by coupling the vehicles in the VOR-database that were involved in the primary collision.

The filtered database was exported to the statistical analyses tool ‘SPSS 12’ [8] and further analysed. For each of the variables a cross-tabulation was made between that variable and SUV vs. passenger car. When in these cross-tabulation a significant correlation between the two variables was detected by the Pearson Chi-squared test, the adjusted residuals (a.r.) were inspected for significant deviation, which are two or more standard deviations from the expected values. The expected values are calculated based on the assumption of independence of two variables.

The VOR database contains accidents with killed (K), seriously injured/hospitalised (SI), slightly injured/non-hospitalised (SLI), unknown injuries and ‘damage only’ (DO). It is known that around 95% of all accidents related to fatalities are registered in the VOR database. It is estimated that 85% of all traffic accidents are included in the database, where a person was injured. For accidents with slight injured persons involved a value of 40% is estimated. Due to representation issues, only accidents in which fatalities and/ or injuries (K+SI+SLI) occurred are discussed in the following section.

For an internal TNO Automotive study every accident was investigated where a SUV was involved and where the Technical department of the police (TOD) made a report. The police officers from the mentioned regions contacted DART when an accident with a SUV happened. The team started an investigation when the criteria are met.

Apart from these cases, DART collected data from old SUV accident cases from 1998 to 2002 in the region “Rotterdam-Rijnmond”. The team did not collect any information at the specific accident location nor inspected the vehicles involved, because of the time gap between the accident occurrence and the investigation. It is obvious that the level of detail of the data will be lower than the normal in-depth research procedure. In total 32 accidents were investigated.

Due to the fact that only SUV accidents were collected and investigated for this part of the study, a comparison between SUVs and cars cannot be made.

RESULTS

National Traffic Accident Statistics Analyses

General analyses on aggressiveness and lethality

A total of 650 SUV accidents are analysed, where fatality and or injury has occurred within the SUV and or the passenger car. With the same criteria 44559 passenger car accidents are analysed. This second group is used as a so-called ‘comparison group’ or ‘control group’.

First co-linearity is treated followed by a general analysis of passenger car and SUV accidents. This general analysis is done, to identify to what extent vehicle accidents might ‘differ from’ or ‘be equal to’ SUV accidents. All variables that were coded in the VOR-database that might influence accident causation or severity were also analysed.

Co-linearity

In the research on aggressiveness of SUVs compared to passenger cars a major problem exists. The main factors which distinguish SUVs from passenger cars (mass, bumper height, stiffness) are highly correlated with these vehicles, except for mass. The large bumper heights and high body stiffness are found in SUVs and not in passenger cars. This high correlation between SUVs and these other parameters makes it impossible to state statistically what causes have a relationship with the aggressiveness. The only statement that can be given is whether SUVs are more aggressive than passenger cars, either compensated for the mass effect or not. It cannot be said that this may be due to bumper height or vehicle stiffness.

Cross-tabulation analysis

For all variables that are coded in the VOR-database that might have a relationship with accident causation or might influence accident severity, cross-tabulations are executed between those variables and the vehicle type, being SUV or passenger car. So a comparison is made between passenger cars and SUVs. All the frequency counts that are presented in the cross-tabulations (N) are the number of SUVs that are involved.

The objective is to find to what extent the SUV crashes differ from passenger car crashes. If no differences are found, this can be considered positive for the analysis, because then both classes are involved in the same type of accidents. When differences are found, they might have influence on accident severity. So in order to say something about possible differences in lethality or aggressiveness, one needs to statistically compensate for these differences. This can be done with a method called (logistic) regression analysis.

Table 1 and 2 show a strong relationship between vehicle mass and gender (gender effect). Female drivers were driving significantly lighter vehicles than male drivers in the accidents that are stored in the database.

Table 1: Gender effect for 'Not SUVs'.

Gender	Mean mass	N	Std. Deviation	Median
Male	1083	26305	248	1050
Female	965	12374	219	932
Unknown	1063	287	226	1050
Total	1045	38966	246	1015

A suv_1 = not SUVs

Table 2: Gender effect for 'SUVs or Pickups'.

Gender	Mean mass	N	Std. Deviation	Median
Male	1690	484	372	1744
Female	1460	152	371	1400
Unknown	1673	5	413	1840
Total	1635	641	384	1660

A suv_1 = SUV or PICKUP

For the following variables that are coded in the VOR-database, no differences between passenger car accidents and SUV accidents were found:

- Type of accident;
- The accident cause;
- Impact location, both bullet and target vehicle;
- Movement of the vehicle(s) after the accident, both bullet and target vehicle;
- Type of manoeuvre;
- Locations on the road before the accident (bullet + target);
- Road type;
- Weather;
- Intended manoeuvre (bullet + target);
- Gender of the driver of the target vehicle;
- Collision opponent.

Also no difference in aggressiveness between SUVs is found based on SUV vehicle mass and SUV bumper heights. So, heavier SUVs are not more aggressive than lighter SUVs. Nor are SUVs with a higher average bumper height more aggressive than SUVs with a lower bumper height.

Factors that did differ significantly between passenger car accidents and SUV accidents are:

- Accident types:
  - Gender of the driver of the bullet vehicle; Significant more male drivers of SUVs (76%) are involved in accidents, for passenger cars this figure is (68%);
  - Speed limit roads; SUVs are more involved in accidents on 80 km/h roads (a.r.=3.1, N=180, 28%) and less on 50 km/h roads (a.r.= -2.4, N=362, 56%);
  - Areas; There are more SUV related collisions found in non-urban areas in comparison to passenger cars, 42% versus 37%, (a.r.=2.6, N=272). Less SUV related collisions are found in urban areas in comparison to passenger cars, 58% versus 63%, (a.r.=-2.6, N=378).
- Accident severity:
  - SUV occupants are less likely to get killed in an accident than passenger car occupants, 0.3% versus 1.3%, (a.r.=-2.3, N=2);
  - SUV occupants have significantly less chance to get killed or seriously injured in case of an accident than passenger car occupants, 8.5% versus 13%, (a.r.=-3.1, N=55);
  - Opponent vehicle occupants have a significantly higher chance to get killed being involved in an accident with a SUV then being involved in a passenger cars accident, 2.6% versus 1.1%, (a.r.=-3.8, N=17);
  - Occupants in the target vehicle have a significant higher chance to get killed or being seriously injured when involved in an accident with a SUV then when involved in a passenger cars accident, 25% versus 19%, (a.r.=-4.2, N=164).

It has to be noted that these differences in accident severity do not yet indicate that there is a higher aggressiveness of SUVs compared with passenger cars. The aggressiveness can only be estimated when taking into account the differences in accident types and differences in vehicle characteristics (mass, geometry and stiffness).

Regression analysis

Logistic regression analysis is a statistical predicting method based on one ore more factors or variables. The method estimates the independent effects of input parameters on the outcome as for example aggressiveness.

- Aggressiveness

A logistic regression analysis was performed to identify to what extent vehicle mass and gender relate to vehicle aggressiveness, more explicit: the probability that a collision opponent will get killed or seriously injured, taking into account vehicle type, mass and gender of the driver. Table 3 shows that increasing mass, increases the probability to get killed or seriously injured (sig< 0.05 and Exp(B)> 1). A significance level less than 0.05, indicates a significant difference with a 95% confidence level. An Exp(B) larger than 1 indicates an increasing probability.

Table 3: Variables in the equation for the prediction of aggressiveness.

								95.0% C.I.for EXP(B)	
		B	S.E.	Wald	Df	Sig.	Exp(B)	Lower	Upper
Step	Mass	.001	.000	98.68	1	.00	1.001	1.000	1.001
1	Gender	.092	.097	.91	1	.34	1.097	.907	1.326
	SUV	-.139	.028	24.85	1	.00	.870	.824	.919
	constant	-1.690	.093	330.29	1	.00	.184		

A Variable(s) entered on step 1: mass, SUV (0= no, 1= yes), gender (male = 0, female = 1)

Females have an injury reducing effect, possibly due to the fact that they drive lighter cars (sig<0.05, Exp(B)<1). Whether the actual vehicle is a SUV, is not relevant (sig>0.05, Exp (B) ~1). The global effect of aggressiveness can be mainly related to vehicle mass, according to the VOR analysed accidents.

- Self-protection (Lethality)

A logistic regression analysis was also performed to identify to what respect vehicle mass and gender relate to vehicle lethality, more explicitly the probability that the driver or passengers in the SUV will get killed or seriously injured. It is found that an increasing mass (sig<0.05, exp(B)< 1) has an injury reducing effect. Gender plays a role but is not significant at the 95% confidence level. Whether the vehicle is a SUV or not is not relevant. Therefore the mass is the most relevant factor for self-protection. A larger vehicle mass reduces the injury level for the occupant, according to the VOR analysed accidents.

Analyses in relation to the collision partner

A total of 650 SUV accidents are analysed, where fatality and or injury has occurred within the SUV and / or the passenger car. With the same criteria 44559 passenger car accidents are analysed. Accidents with the following collision partners are analysed in this section:

- Passenger cars;
- Vans (Light Trucks);
- Two-wheeler;
- Pedestrians.

Passenger cars

The number of SUVs involved in a collision with a passenger car is 192 and the number of passenger car to passenger car collisions equals 19739.

For both SUVs and passenger cars the head-tail collisions are most frequent (45%), followed by side impacts (40%) and thereafter frontal impacts (12%). The parking accidents occur in 3% of the cases. The impact location on the mid-front is more pronounced (45%). With SUVs the impact point is somewhat more to the right-front, 10% versus 6% (a.r = 2.6, N=28). More male drivers are involved in relation to passenger-drivers, 73% versus 67% (a.r.=2.0, N=212).

Related to the type of road and road side, SUVs are significantly more often involved in accidents with passenger cars on the right side of normal two lane roads, 71% versus 65%, (a.r.=2.1, N=207). There is a slight indication that SUVs are more involved on 80 km/h roads, 30% versus 26% (a.r.=1.5, N=88). Most accidents occur in urban areas on 50 km/h roads (51%).

The probability to get killed, for both vehicles, in an accident with SUV involvement is not higher than in accidents with only passenger car involvement. There is however a trend that is confirmed when taking into account severe injuries in the analysis.

The probability to get killed and/or seriously injured for:

- SUV passengers is significantly lower than for the persons in passenger cars, 8.2% versus 15% (a.r.= -3.0, N =24). This effect disappears in a logistic regression analysis with the vehicle mass taken into account;

- The passengers in the collision opponent is significantly higher with a SUV collision related to a passenger car to passenger car collision, 21% versus 15%, (a.r.=3.0, N=61).

Logistic regression analysis shows that mass is the main predictor for accident severity. The vehicle type is not anymore relevant and the difference found above is caused by the higher vehicle mass compared to the mean mass of passenger cars

Vans (Light Trucks)

The number of SUVs involved in an accident related to Vans is 34 and the number of passenger car within this type of accident equals 2574. The numbers are small and the results are therefore presented as trends and not as real significant differences.

There is a trend towards more head/tail accidents with SUVs, in comparison to passenger car accidents, 65% versus 47%, (a.r.=2.0, N=22) and towards slightly less side impacts, 21% versus 40%, (a.r.=-2.3, N=7). There is more often a collision point on multiple locations on the Van in collisions with SUVs (24%), in comparison with passenger car – Van accidents (5%) (a.r.= 4.7, N=8).

More male SUV drivers are involved in accidents with Vans then male passenger car drivers, 85% versus 66%, (a.r.=2.4, N=29). A strange observation is that in Van - SUV accidents, the driver of the Van is percentage wise more often a female driver (32%) in comparison with car – Van accidents (9%) (a.r.= 4.5, N = 11). This difference cannot easily be explained.

No difference is found in road type, which is in contradiction to other categories.

There is no difference in aggressiveness between SUVs and passenger cars against Vans. There seems to be a light trend towards better self-protections for SUV occupants (a.r.= -2.1, 6% vs. 20% fatal and/or seriously injured, N= 2 vs. N=521). But when vehicle mass is taken into account in a regression analysis, this effect disappears.

Two-wheelers

The two-wheeler selection covers: motorcycles, mopeds, mofas and bicycles. The number of SUVs involved in an accident with a two-wheeler is 224 and the number of passenger cars within this type of accident equals 15292.

Fatality or injury rate of the two-wheeler rider related to the SUV accident is significantly higher than related to a passenger car accident:

- Fatality rate SUV versus passenger car, respectively 4.5% and 1.6% (a.r.=3.3, N=10);
- Fatality or seriously injured rate SUV versus passenger car, respectively 36% and 29% (a.r.=2.2, N=80).

The injury levels of the SUV occupant do not differ significantly from car occupants in two-wheeler accidents. Binary logistic regression analysis shows again that vehicle mass is the main indicator for injury severity.

Gender of the SUV driver is not a significant factor in two-wheeler accidents.

Pedestrians

The number of SUVs involved in an accident with a pedestrian is 32 and the number of passenger cars within this type of accident equals 1756.

There is no difference in male SUV or passenger car drivers involved in accidents with pedestrians.

The probability to get killed or seriously injured for pedestrians is independent of the vehicle type (SUV or passenger car). The numbers are too small to draw a conclusion. There seems to be a trend towards higher probability for pedestrians to get killed or seriously injured in an accident with a SUV (56% versus 42%, a.r.= 1.6, N=18).

However, when a logistic regression analysis is done, a trend is spotted for higher aggressiveness of SUVs (sig<0.1, 90% confidence interval), due to the compensation of gender (sig<0.05, females reduce accident severity possibly due to lower vehicle weight). Therefore, for pedestrians the geometry or stiffness of a SUV may be of influence.

TNO Automotive In-depth Accident Database analyses

<u>*Damages*</u>

For the SUVs 47 damage locations were identified. In Table 4 the number of deformations per collision partner type is shown. Most frequent are damages on cars followed by objects or the ground and powered two-wheelers.

'SUV - Car' deformation locations

Combined deformation locations from CDC-coding [9] show for 'SUV - Car' impacts, that cars seem to be more frequently damaged on the side (8+4) than SUVs (4+2) and that SUVs seem to be more frequently damaged from the back (6 versus

Table 4: Number of collisions per collision partner type.

Collision partner	Frequency	Percent	Valid Percent	Cumulative Percent
Truck	2	4.3	4.3	4.3
Powered two-wheeler	10	21.3	21.3	25.5
Object or ground	11	23.4	23.4	48.9
Van	2	4.3	4.3	53.2
Car or car-derivative	22	46.8	46.8	100.0
Total	47	100.0	100.0	

0). There seems to be no real difference in frequencies of frontal interactions. Five damages are caused by side to side interactions. In three cases no damages are found on the SUV, while the car is damaged.

When vertical and lateral locations are taken into account, it can be checked if over-ride situations occur. There is a weak indication for some over-ride problems in collisions between cars and SUVs. (More proof for under-ride will be given in the section "Case-by-case analysis from accident photographs") Most frequently the lower half of both vehicles is damaged (E). In five cases the total height of the car is damaged (A); for the SUV only two damages are coded over the total height (A).

'SUV - Object' deformation locations

In four cases an impact occurred but no deformation on the SUV was found. The front and left side seem to be most frequently damaged in a collision with an object.

'SUV - Powered two-wheeler' deformation locations

The deformation locations on the 'powered two-wheelers' seem to concentrate on the front of the vehicle. In impacts with powered two-wheelers, there seems to be a tendency that the full height of the two-wheeler is damaged (A), while on the SUV only the lower half or bumper area is damaged (E and L).

<u>Injury levels</u>

For the SUV in-depth research, it was tried to obtain the injuries from the victims. In 21 accidents of the 32 investigated accidents, persons were injured. 40 known injuries were coded and from eight persons it was known that they were injured but the injury level was unknown.

'SUV - Powered two-wheeler' injury levels

The most injuries caused by the vehicle side are abdominal injuries and injuries on the extremities (mostly fractures). Injuries resulting from the contact with the pavement are various. The injury levels for the powered two-wheeler rider vary from AIS 1 to AIS 4. Most frequently AIS 2 injuries were noticed, which are mainly fractures and some dislocations. AIS 4 injuries are a lung hemothorax with hemomediastinum and a gallbladder laceration.

'SUV - Car' injury levels

Unfortunately, for car occupants many injury causes are unknown. Injuries caused by the car interior, are mainly injuries on head and face. AIS levels for the car occupant are at maximum AIS 3. Here, the AIS3 injury is an unspecified brain injury. Also some low injury spine and neck injuries were found.

SUV occupants were hardly injured in the investigated accidents; only some bruises were found and some unknown injuries. The injuries were obviously caused by the SUV interior: one by the steering wheel and one by the front door. It seems that injury levels for the SUV occupant might be lower than that of their collision partners; SUV occupants are more frequently uninjured, which might point to a safer environment for the SUV occupant.

<u>Case-by-case analysis from accident photographs</u>

The photographs of accidents from the TNO Automotive In-depth database concerning SUVs and from the European Accident Causation Study (EACS) project were used for further analysis of the vehicles' damage. In total, 37 cases were analysed from which 10 from the EACS project. The pictures were taken by the various research groups (TNO Automotive and/or other European institutes) or by the Dutch accident police departments during the on-scene inspections, the reconstruction of the impact position of the vehicles, and/or the technical inspection of the vehicles.

The 37 cases can be divided into five categories:

- Frontal/rear impact (n=14);
- Side impact (n=9);
- Rollover (n=3);

- Impact with two-wheelers (n=8);
- Impact with pedestrians (n=3).

The results of the photographs' analysis can be divided into the following categories:
- Bumper height;
- Protruding objects;
- Stiffness of the SUV;
- Rollover of SUVs.

Bumper height

The height of the bumper of the SUV was a parameter, which influenced the development of the crash in many accidents. The accident configurations that have been studied are head-on collision (SUV versus passenger car), rear-end collision (SUV versus passenger car and vice versa) and side impact (SUV versus passenger car and vice versa).

Figure 1 illustrates the height of the lowest point of the bumper of a SUV from the ground compared to the height of the bumper of a passenger car. This difference exists because the vehicles are built as terrain vehicles. A terrain vehicle and now the SUV too is equipped with large diameter tires and with big stroke shock absorbers so the ground clearance of the frame and the components underneath the vehicle needs to be high enough to avoid contact with the rough surface during off-road driving.

Another accident scenario where the SUV runs into the rear of a Van was also observed. The SUV hits the rear door because of the high positioned SUV bumper and the low positioned bumper of the Van. The Van normally has a low height of the loading floor from the ground, which makes the loading of the vehicle easier. A possible danger in this case is that the rear door can easily collapse during an impact and the SUV may penetrate the loading compartment. Some Vans are modified by the manufacturer into 'nine-person' buses. The rear row of seats (usually three seats) is placed very close to the rear door and in case of an impact this may cause injuries.

Bull-bars and other protruding objects

Many objects installed on a SUV are observed in the pictures, which can increase the severity of an accident. A frequently seen object is the 'Bull-bar'. The shape and the material of the bull-bar are the two important parameters. The danger of this construction is that the bar will apply the impact force and not a broad surface. This will increase the local penetration depth. In two-wheeler and pedestrian accident the bull-bar will increase the chance for a bone fracture of the rider and the pedestrian.

In many cases the pipes of the bull-bar were not deformed during the impact. The difference in

Figure 1. Difference in the height of the bumpers.

stiffness between the bull-bar and the impact partner was huge. As a result of this, the deformation of the partner increased. Bull-bars must be banned from vehicles in normal traffic or more attention must be paid to the design of the bull-bars and to the choice of the material.

It is noticed from the analysis of the photographs that when a passenger car crashes into the rear of the SUV, the front of the passenger car dives under the rear of the SUV (Figure 2-left). This is even more serious when the passenger car decelerates before the impact. The front suspension system is compressed, the front of the vehicle lowers towards the ground and the passenger car dives under and lifts the rear end of the SUV during the impact (Figure 2-right). The disadvantage in both scenarios is that energy is absorbed by the top of the hood, whereas the hood is not designed for this purpose and this gives huge deformations. The easily deformed metal sheet could cause injuries to the occupants.

Another object that could be dangerous is the outside mounted spare wheel at the rear door of the SUV. When a passenger car crashes into the rear of a SUV, the spare wheel will push the hood towards the rear (Figure 2-right). The deformed or displaced hood may break the windshield and may come through the occupant's compartment. The spare wheel largely increases the under run effect.

Figure 2. Under run effect.

When a high-fronted vehicle (such as a truck, a bus, or van) crashes into the back of a SUV, the spare wheel will move into the SUV (the wheel is stiffer than the door), deforming the rear door at the same time. The wheel is protruding the rear end approximately 300 to 400 mm and therefore it increases the deformation extent 300 to 400 mm locally. The passengers on the rear seat are more endangered to sustain injuries.

Ornaments on the top of the hood (fastened with screws) or fog lights attached to the bull-bar may cause or increase the injuries during an impact with a two-wheeler rider or a pedestrian. Foldable ornaments and fog lights are an easy solution, but this solution is effective only during a frontal impact or only during a side impact with the ornament or the lights, depending on the direction in which they fold.

Two other objects that may be found at the SUV front are a towing hook and/or a winch. Because of their shape and stiffness and the fact that these objects are rigidly attached to the longitudinal ladder frame, these objects may become very dangerous during a side impact or during an impact with a pedestrian.

Figure 3. The front of a small passenger car that drove into the back of a SUV.

Stiffness of the SUV

An important factor in compatibility is the crash stiffness of the SUV. SUVs are much stiffer compared to passenger cars. This is caused by the principle of chassis construction. Most SUVs are built on a ladder chassis with stiff beams, where passenger cars in general have a uni-body construction.

The SUV with the ladder chassis construction is more aggressive, due to the fact that the beams of the ladder chassis are very stiff. Also from the pictures of the real accidents (Figure 3) it can be seen that the damage to the SUVs is rather small, where the target vehicle has extensive damage, in frontal accidents.

Rollover of SUVs

SUVs tend to rollover more easily due to a higher centre of gravity and this type of accident is of special interest from the fact that a relatively high percentage of the SUV occupants die. The problem with rollover is two-fold:

- The deformation of the roof of the vehicle results to a little survival space at the top. This is due to the construction of the car, such as lowering the centre of gravity by reducing the weight at the upper part (A-, B- and C-pillar). In case of rollover, the construction is not strong enough to resist the impact. An example is the left picture in Figure 4;
- Most common is the ejection of the SUV passengers in a rollover, especially in the case of not wearing the safety belt. In the left picture in Figure 4 the windows are broken and ejection may occur. From the in-depth TNO rollover cases no fatalities are reported.

CONCLUSIONS

Figure 4. Rolled over SUV, left a frontal rollover, right a side rollover.

SUV's are significantly more aggressive against vulnerable road users. Problems with SUV crashes to other vehicles are related amongst others to compatibility, except for commercial vehicles. However in this study no difference is found between heavy passenger cars and SUVs. SUVs are about as heavy as the average full-size passenger car. So the same mass difference occurs between passenger car classes (e.g. full-size and small cars).

Although the bumper height is about 20% higher compared to passenger cars, this difference could not directly be related to an increase in injury severity in this study due to the lack of data. Nevertheless, based on accident pictures and other investigations, it is believed that mass, frontal stiffness and geometry factors play a role in the compatibility between SUVs and other road users.

Regarding accidents with injurious outcome, SUVs are generally involved in the same kind of crashes as normal passenger cars. Side impacts and 'head – tail' impacts are most frequent, followed by frontal impacts. Collisions between SUVs and passenger cars are relatively more frequent on 80 km/h roads, for SUV's against trucks however this trend could not be observed. The speed of the SUV (and of a passenger car) has a significant influence on the prediction for the collision opponent to get killed or seriously injured.

Mass of the striking vehicle is a factor in the prediction of accident severity. The accident data used in this study did not allow to distinguish whether this 'mass' aspect contains hidden stiffness and geometrical aspects such as bonnet height and bumper height, due to high correlation between mass, stiffness and geometrical aspects.

For aggressiveness it was found that striking vehicle mass is the main predictor for the accident severity. A higher vehicle mass as such increases the accident severity, whatever the type of vehicle (SUV or passenger car). From the 32 in-depth cases studied, the resulting injuries of car occupants observed were mainly to head and face and at maximum AIS 3 (serious). SUV are significantly more aggressive towards pedestrians and powered two-wheeler riders than passenger cars, even when compensated for the mass differences. The in-depth data showed that the injury of powered two-wheeler riders were mainly bone fractures. The level varied from AIS 1 (light) to AIS 4 (fatal). With under-run accidents by passenger cars the difference in the height of structural parts, but also other external geometric features of the SUV may play an important role in the damage and injury sustained.

With respect to fatality there is tendency towards a slightly better crash protection for the SUV driver and his passengers, than for the driver and passengers of a 'normal' passenger car. SUV occupants seem to be more frequently not injured in a crash. This might indicate a safer environment for the SUV occupant, but it is most probably due to the higher vehicle mass, less absorbed energy and resulting intrusions in a crash.

With respect to the gender of the driver, SUVs are more frequently driven by males than by females. In the analysed accidents males are also found to generally drive heavier vehicles and for that reason they are found to be a significant factor in the prediction of fatality and serious injuries for the occupant(s) in the struck vehicle. In this respect, female SUV drivers significantly decrease the probability at fatal or serious injuries for struck car occupants. This effect might be partly due to the fact that in general women involved in accidents drive significantly lighter cars than males involved in accidents.

RECOMMENDATIONS

Design recommendations

Concerning the aggressiveness, the front and rear ladder chassis construction could be redesigned to a less aggressive during an impact with a passenger car. The height of the bumper and other load bearing components of SUVs could be made more compatible to other road vehicles.

Ornaments and fog lights could be integrated in the front and the spare wheel could be placed within the vehicle, in a similar way as the spare wheel of the passenger cars.

The use of a winch needs to be considered for strictly limited or no admittance on public roads. An easily demountable version of the winch should be developed.

Attention should be paid to the bull-bar. A bull-bar is of no use in road traffic. In principle the bull-bar is an add-on structure and was not part of the safety considerations by the manufacturer. A closer bull-bar construction, allowing less space in between the bars and not protruding the width of the vehicle should be designed. A suggestion could be a more restricted regulation, which would allow the use of a bull-bar only if it has no negative effect on the safety of other road-users.

With respect to lethality, a less deformable SUV roof and upper pillars have to be designed, to prevent the collapse of the roof during rollover accidents.

Recommendations to improve the analyses

The effect of mass needs further investigation with a study in which passenger cars and SUVs in identical mass-classes should be compared. The two groups need to be of equal mass-distribution. Difference between the two categories could then be explained by geometry (e.g. bumper height, height of principal force) or stiffness characteristics.

The effect of gender needs to be further investigated through a so called ‘control group’. Video shots at random locations should be able to give information about the frequency of male and female drivers in passenger cars and SUVs. Compared with accident data, this information could give valuable information about driving behaviour differences between men and women, and information about average vehicle mass in these categories.

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INJURY PATTERNS AND EFFECTIVE COUNTERMEASURES FOR VEHICLE COLLISION COMPATIBILITY

Mukul K. Verma, Joseph P. Lavelle, Soo A. Tan, Robert C. Lange
General Motors Corporation, USA
Paper Number 05-0173

ABSTRACT

This paper examines the NASS-CDS statistics to identify the significant parameters associated with injuries in LTV to car frontal collisions. These parameters of interest are the ΔV of the colliding vehicles, the direction of impact as well as any under-ride of the smaller vehicle. It is observed that the cumulative ΔV curve of car occupants in frontal tow-away collisions with LTVs becomes asymptotic at 30 miles per hour and that over 97% of those car occupants are in cars with a ΔV of 35 mph or less. The relationship of injuries with the reported under-ride in the NASS database is more complex and in several ΔV ranges, the presence of under-ride is related to a lower risk of injuries. Based on these findings, evaluations of compatibility improvement are conducted for frontal impact between an LTV and a small car at approximate ΔV of 35 mph and intrusion levels are calculated for the struck car. It is concluded from the data presented here that lowering the height of LTVs to increase the vertical overlap with a smaller vehicle may, in many cases, increase the intrusion levels in the smaller vehicle as well as increase the crash energy in the smaller vehicle. The addition of a secondary structure to LTVs for the purpose of increasing structural interaction is also investigated and it is shown that the effect of this in the studied cases is to reduce the calculated intrusion in the smaller vehicle.

INTRODUCTION

Several studies published in the recent literature have discussed the factors influencing collision compatibility between different sized automobiles and the possible ways of improving this compatibility. Although most of the societal harm in vehicle-to-vehicle collisions is attributable to lateral impacts[1], almost all of the published studies have looked at frontal impacts only.

It is important to emphasize that the objective of 'improved collision compatibility between vehicles' is that of improving the safety of the occupants of a smaller vehicle in collisions against a larger automobile. Therefore, any criteria proposed as measurement of compatibility improvement must demonstrate strong, monotonic relationship to the reduction of injury probability of occupants in the smaller vehicle. Such relationship is yet to be demonstrated for any of the criteria or test procedures published so far.

Several authors[2-5] have suggested measurements of compatibility in frontal crashes by using data from discrete load cells on a fixed barrier, the test procedure consisting of the larger vehicle in the collision pair (often referred to as 'the striking vehicle') being impacted into such a barrier at a certain speed. These barriers have generally consisted of a fixed, rigid surface with or without a layer of deformable material. The quantities measured in such tests are of course limited to forces at the various load cells and the crush of the barrier material. The proposed measures of collision compatibility have been mathematical functions of the measured quantities, e.g. height of force, peak force levels, homogeneity of force distribution, etc. As mentioned above, none of these mathematical functions meet the criteria[6] necessary to be a reliable indicator of collision compatibility of the vehicles. Several other published studies have been attempted to identify the significant factors influencing the vehicle compatibility from investigation of vehicle-to-vehicle impacts[7, 8].

The present paper discusses the definition of proper evaluation conditions that are representative of crash statistics in the USA. The possible solutions for improving compatibility are then studied in these 'field representative' conditions. Of course, collision compatibility is only one aspect of the total traffic safety and it is necessary that any improvements in collision compatibility be also evaluated for the effect on the overall safety.

FRONT-END FORCES OF A VEHICLE

Considerable attention has been paid in the published literature to the premise that the measurement of the forces exerted by a vehicle in a frontal impact against a barrier can be transformed into a compatibility measurement. However, an examination of the front structure of automobiles shows that the principal load paths in frontal crashes consist of structural components with generally hollow sections (such as the frame rail, rockers, engine cradle, etc) and other 'non-structural' components (such as engine, transmission, tires, etc). The forces generated in any crash are then the aggregation of the response of all these components of the automobile as well as those from the other collision partner. Since the structural properties of the vehicle components are highly nonlinear functions of the loading direction, load magnitudes, the loading area, time, etc, it is to be expected that the forces generated by the vehicle in an impact are also time- and space-dependent, nonlinear functions of 'what' these components impact and 'how' they interact (the direction of loading, deformation modes, interaction dynamics such as sliding, rotating, etc).

For such nonlinear, highly directional and non-uniform structures, it is not possible to predict the force generated in a specific mode of impact from that measured in another mode. Thus, the forces in a vehicle-to-vehicle impact will be vastly different from those generated in a fixed barrier impact. Similarly, the forces in vehicle-to-vehicle impact will be dependent on the location of impact, the direction of impact, the speed etc.

The design of front-end structures is governed by the fundamental principle of the crashworthiness in that they have to meet the various regulatory and non-regulatory requirements for front crashes. Thus, these front structures dissipate the total energy of the crash in the crush space available in the vehicle in the most efficient manner possible. The crash energy (or the pre-impact kinetic energy) is proportional to the mass of the vehicle. This relationship has been discussed in an earlier publication[9] and is also supported by available test results, e.g. those in the US NCAP database of the National Highway Traffic Safety Administration. Since the pre-impact kinetic energy of the vehicle is translated principally into structural deformation of the vehicle (ignoring the small portion used in post-crash translation and into other forms of energy), it is to be expected that the average force (averaged over the crush depth) measured on the barrier will be proportional to the mass of the vehicle, other factors remaining the same.

That such is indeed the case[9] is shown in Figure 1, which is a plot of the vehicle mass versus the 'average force' calculated from frontal NCAP tests. This 'average force' is not a physical parameter but a hypothetical number which, when multiplied by the total distance of crush of the vehicle, is indicative of the pre-impact kinetic energy of the vehicle.

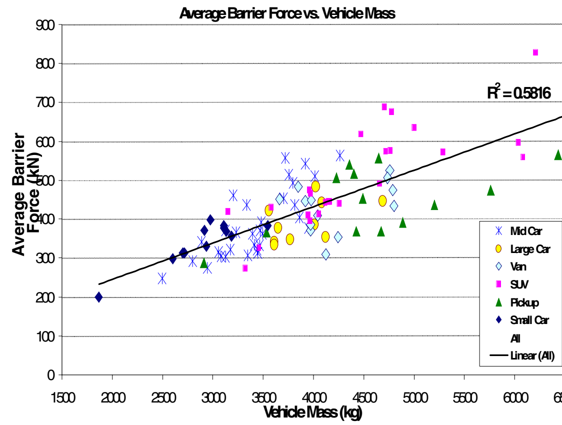

Figure 1: Relationship of Front-end force to Vehicle Mass in NCAP tests

As is to be expected, a slightly stronger correlation exists between the average force and the parameter 'vehicle mass divided by the dynamic crush distance of the vehicle (Figure 2). The relatively slight change of correlation (when the crush distance is used as one

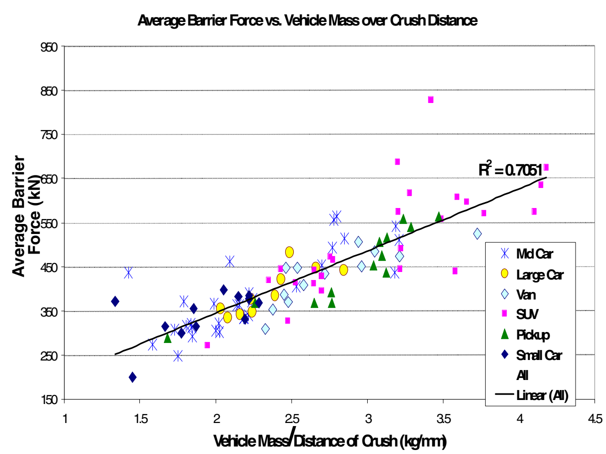

Figure 2: Front end Force relationship to Mass and crush distance in NCAP Tests

of the variables) is an indication that this parameter (vehicle's crush space) is relatively invariant for the vehicle population.

If the vehicle were to impact another vehicle, the forces generated will be different from those measured against a fixed barrier for the reasons mentioned earlier. It is important, therefore that determination of collision compatibility be based on the dynamics of vehicle-to-vehicle crash and that any measurement of compatibility improvement be ultimately linked to evaluation in a vehicle-to-vehicle crash in a ‘field representative’ test condition.

FIELD REPRESENTATIVE TEST CONDITION

Shown in Figure 3 is the distribution of harm in

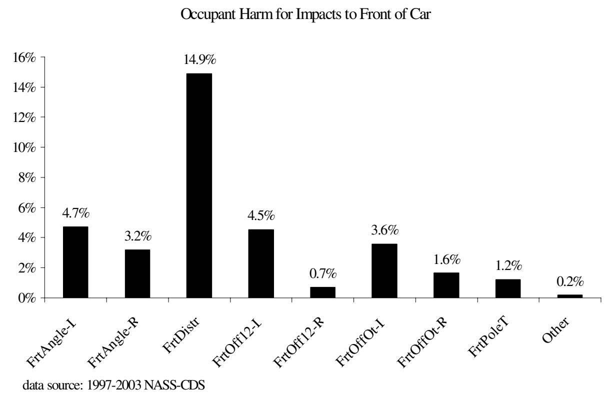

Figure 3: Distribution of harm in LTV-to-car front impacts by location & direction

frontal crashes between light truck based vehicles (referred to as LTVs) and passenger cars, obtained from the 1997-2003 NASS-CDS database. It is observed that the category of ‘Front Distributed’ crashes is the largest single category associated with harm in frontal collisions. Similarly, the estimated change in velocity (ΔV) of cars in frontal impacts with LTVs is shown in Figure 4 from the same

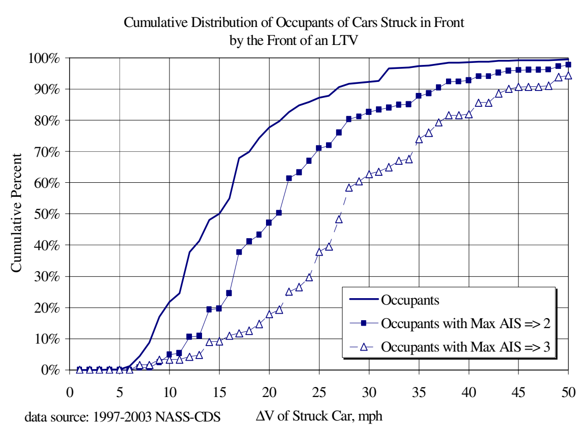

Figure 4: ΔV of cars; Frontal Collisions with LTV

NASS-CDS database. It is seen that for these crashes, more than ninety percent of the occupants (and sixty three percent of the occupants with reported injuries of AIS greater than or equal to 3) were in cars with a ΔV of 30 mph or less. A threshold of ΔV =35mph includes over ninety-seven percent of all the occupants and about seventy four percent of those occupants where the injury reported was of AIS $\geq$ 3.

It can therefore be stated that a ‘field representative’ condition for evaluation of collision compatibility is a full frontal test between two vehicles where the ΔV in the struck car is 35 mph

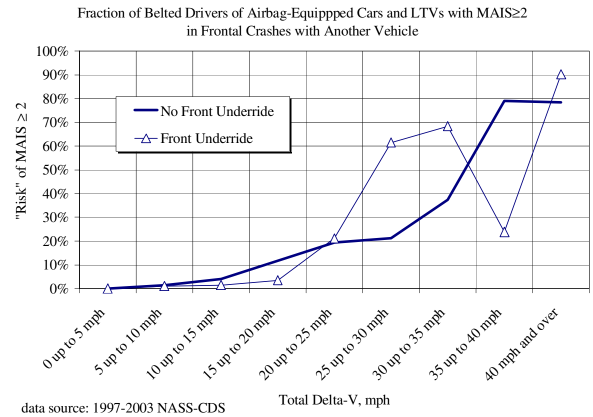

Figure 5: Vehicle Under-ride and MAIS Risk

There is no consistent relationship observed between under-ride reported in the database and the probability of injury (Figure 5).

COUNTERMEASURES FOR COMPATIBILITY IMPROVEMENT

For two vehicles of different heights, ensuring the structural interaction between the colliding vehicles is generally considered to be a step towards increased compatibility. For the US fleet, the issue of compatibility is often interpreted to be that of collision between LTVs and passenger cars and the improved structural interaction has been mentioned as a step towards preventing the higher LTV over-riding a lower automobile.

From an examination of the automobile structures, it is easy to conclude that any such ‘increased structural interaction between vehicles’ needs to be between the primary structures of the vehicles (and not between the bumpers since the bumper carry a very small part of the load in collisions at speeds being considered here). One possibility of achieving such increased structural interaction is by aligning the primary structures of the two vehicles. For a high LTV, this may be achieved by requiring that the height of the primary structure be lowered. Alternatively, this may be achieved by adding properly designed secondary structures to the LTV. Both these options are examined here.

Lowered Height of LTVs

A simulation of frontal impact between an LTV and a passenger car was conducted using finite element models of the vehicles. Both the vehicles were moving towards each other at 30 mph prior to the impact (Figure 6).

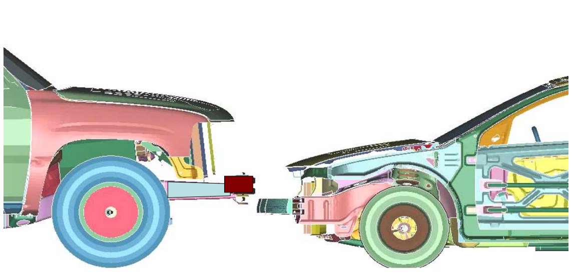

Figure 6: Simulation of LTV-to-Car Frontal impact

For this study, the LTV height was varied to obtain the following four cases (shown in Figures 7a and 7b with the bumpers of both vehicles hidden from view):
a) Baseline- No overlap between the frame rails (primary load carrying structures of the LTV and of the car);
b) Full overlap-The LTV was lowered so that its frame rail fully was fully overlapped by the car frame rail (centerlines of the frame rails of the two vehicles were aligned);

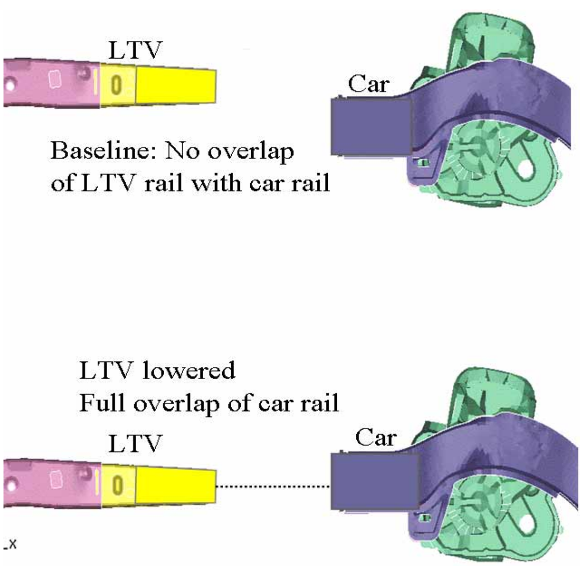

Figure 7a: Baseline and Full overlap cases of LTV rail with Car Rail

c) Large (>50% overlap) - The LTV was lowered so that the car rail overlapped more than 50% of the depth of the LTV rail (bottom of LTV rail was aligned with the centerline of car rail);

d) 50% overlap - The LTV was lowered so that the car rail structure overlapped 50% of the depth of the LTV rail (centerline of the LTV rail was aligned with the top of the car rail).

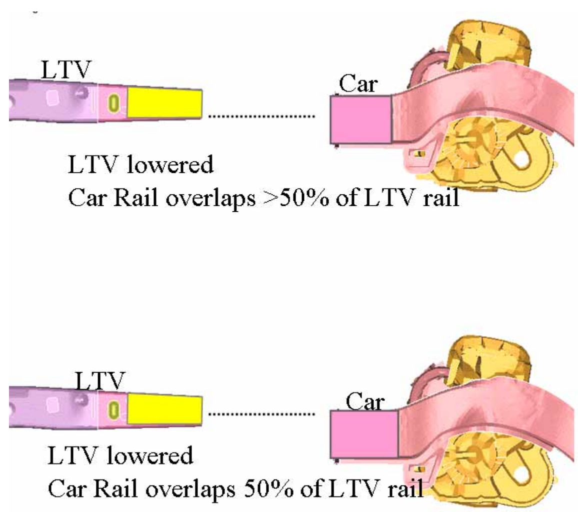

Figure 7b: Partial overlap cases of LTV rail with Car Rail

The calculated intrusions at several points in the struck car are presented in Figure 8 for this simulation of frontal impact.

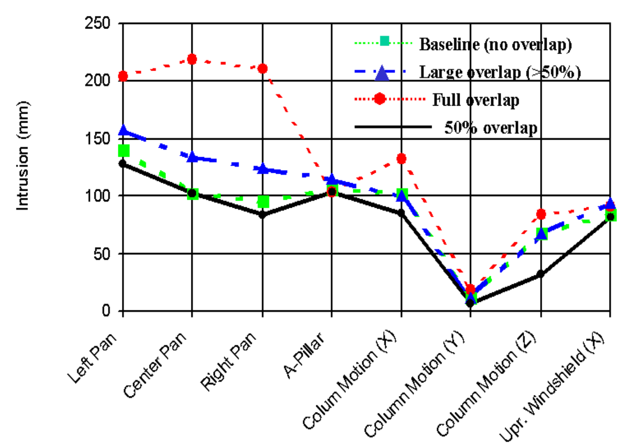

Figure 8: Effect of Increased overlap on Struck Car

It is observed that lowering the LTV to obtain larger structural overlap between the vehicles generally increases the intrusions in the passenger car. The full overlap of the structures of the two vehicles produces the highest amounts of intrusion in the struck car in the present study. It is only in the case of the 50%

overlap that a slight reduction in intrusion in the car is obtained.

Similar conclusions are drawn from an examination of the energy distribution between the two vehicles. The total energy just prior to the impact equals the sum of kinetic energies of the two vehicles. This energy is translated during the impact into the following components-
a) energy dissipated in the structural deformations in the car (shown as 'car energy') and the truck (shown as 'truck energy') ,
b) energy dissipated in the motion of the vehicles during the impact (shown as final 'kinetic energy'); and
c) energy dissipated in other forms (non mechanical, etc).

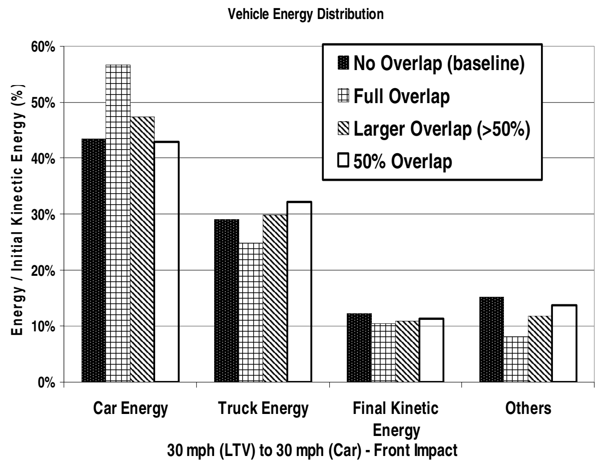

Figure 9: Effect of Structural overlap on energy sharing between two vehicles

Figure 9 show that larger structural overlaps between the two vehicle results in more energy being transferred into the structural deformation of the car (as compared to the baseline case of no vertical overlap). Again, a small reduction in the energy share of the car is observed only for the case of the 50% overlap of the LTV primary structure.

The above conclusion that increasing the vertical overlap between two vehicles of dissimilar mass may not improve the collision compatibility between the vehicles is generally supported by the published[8] test data in the literature.

SECONDARY STRUCTURES ADDED TO LTV

Addition of a 'secondary structure' to the frame rail of a higher vehicle is a possible solution for increasing the structural interaction[6] of such vehicle with a lower vehicle. One of the possible mechanisms by which such added secondary structures improve the interaction between the two vehicles is that, when impacted by the frame rail of the passenger car, these secondary structures generate a bending moment on

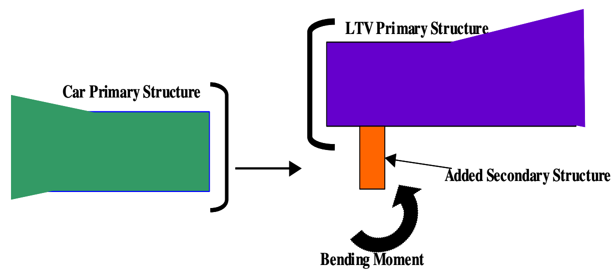

Figure 10: Secondary Structures Added to LTV

the frame rail of the LTV. This of course requires that the secondary structure be of sufficient strength so as to not fail prior to the bending of LTV rail. There may also be other structural interactions. Since the loads required to initiate bending of hollow-sectioned structures are generally lower than the axial crush strength, the effect of secondary structures is to cause higher deformation in the LTV rail in an impact with a lighter car. This has been studied here for impacts between two vehicles. The 'base LTV' was selected to represent a 'mid size Sports Utility Vehicle' in the US. A properly designed secondary structure was added to the LTV (Figure 11) to increase the structural engagement between the primary structures of the LTV and the passenger car.

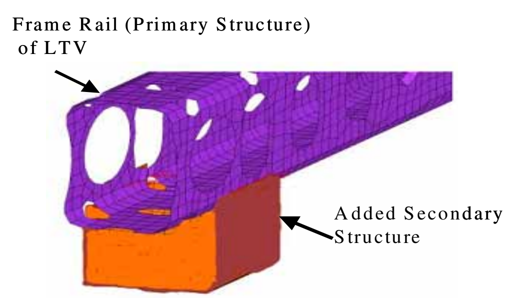

Figure 11: Secondary Structure added to LTV for Increased structural engagement

The impact conditions investigated in the present case (Figure 12) were (a) full frontal crash between the two vehicles, and (b) a 50% offset impact between the vehicles. The LTV and the passenger car

Results from this investigation are shown in Figure 13 for the calculated intrusions at several points in the struck car. For the full frontal impact between the

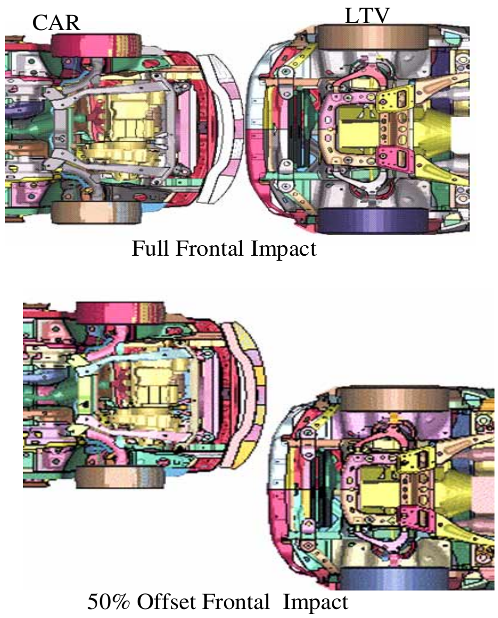

Figure 12: Frontal Impacts between two vehicles

two vehicles, the addition of the secondary structure to LTV leads to reduced intrusion levels in the struck car. Similar conclusions regarding the effect of the added secondary structure are also observed for the

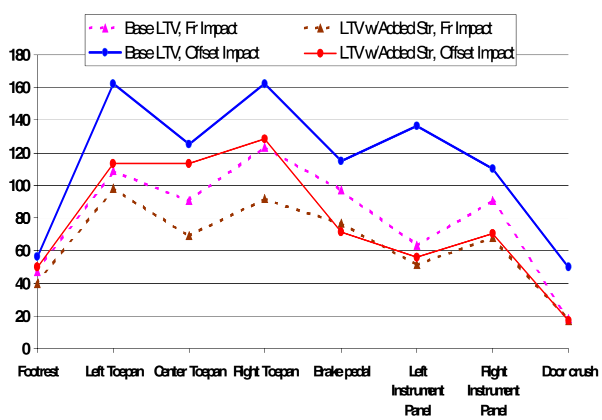

Figure 13: Effect of Added Structure to LTV on passenger car intrusions

the case of offset frontal impact between the two vehicles.

In contrast to the effect observed from lowering LTVs, the effect of adding secondary structure to the LTV is thus found to be preferable in that the intrusion levels in the lighter vehicle are lowered by the added secondary structure.

CONCLUSIONS

This paper discusses the approaches to enhancing geometrical interaction in frontal collision between vehicles. The main points are the following:

1. Evaluation conditions have been identified from. NASS-CDS statistics and these may be considered to be 'field representative' for evaluation of frontal collision compatibility.

2. Forces generated by a vehicle in a barrier test are proportional to the mass of the vehicle and are determined by the various barrier test requirements. These forces and the associated parameters as measured by load cells on a fixed barrier are unlikely to be representative of vehicle-to-vehicle collision compatibility.

3. Lowering the height of larger vehicles to increase their structural interaction with smaller vehicles may not produce desirable results in many cases.

4. The addition of appropriately designed secondary structures to larger vehicles has been shown to increase the structural interaction while reducing the calculated intrusions in the smaller vehicle. This approach needs to be explored further as a possible solution to improving collision compatibility between vehicles.

Further studies are required to assure that the approaches mentioned here improve 'partner protection' without any significant degradation of self-protection in automobiles and thus help achieve the goal of automotive safety of reducing the overall number of injuries and fatalities.

ACKNOWLEDGEMENT

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RESEARCH ON STIFFNESS MATCHING BETWEEN VEHICLES FOR FRONTAL IMPACT COMPATIBILITY

Taisuke WATANABE
Shigeru HIRAYAMA
Kazuhiro OBAYASHI
Tomosaburo OKABE
Nissan Motor Co., Ltd.
Japan
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ABSTRACT

To achieve good frontal impact compatibility, it is necessary to help match stiffness between vehicles in addition to the enhancement of structural interaction. In this paper, the issues of helping stiffness matching in frontal SUV-to-car impacts were studied using MADYMO vehicle simulation and MADYMO occupant dummy simulation.

1. INTRODUCTION

The introduction of various vehicle impact safety regulations and new car assessment programs in addition to automobile manufacturers' continuing efforts to improve vehicle safety performance have led to the significant improvement of vehicle safety performance over the past years. Especially the protection performance that a vehicle helps provide for its own occupants, which is referred to as self-protection, has been improved. Additionally, in recent years, the further improvement of the protection performance that a vehicle helps provide for the ‘opponent’ vehicle's occupants, which is referred to as partner-protection, and the optimization of both self-protection and partner-protection is recognized as an approach to further help enhance vehicle safety performance. This approach is generally called compatibility.

Generally, it is thought that enhancing structural interaction between the front-end structures of vehicles is a first step to achieve compatibility and helping match stiffness between vehicles is a next step [1]. Approaches to enhance structural interaction have been proposed and discussed [2]-[8]. On the other hand, researches on helping match stiffness seem few.

In this paper, the following issues in the case where SUV impacted on car under the condition shown in Table 1 were quantitatively studied.

i) Required the increase of the car body stiffness to lower the deformation of car body.

ii) Influence of the increase of car body stiffness on occupant injury indexes in fixed-barrier impact tests.

For the purpose of focusing on stiffness-matching, an assumption was set in following study that structural interaction is satisfactory. The study was done using MADYMO vehicle model (Figure 1), in which vehicle components were modeled as multi-DOF masses and nonlinear-springs, and MADYMO occupant dummy model (Figure 2). Each MADYMO vehicle model had been correlated with the corresponding fixed-barrier physical impact tests.

Table 1. Selected vehicles and impact condition

Vehicle type	SUV	Car (Middle-sized sedan)
Kerb mass	2,500 kg	1,400 kg
Impact speed	56km/h each vehicle (closing speed=112km/h)	
Overlap ratio	50% of car’s width	

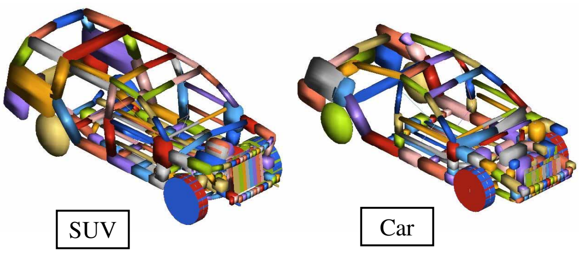

Figure 1. MADYMO vehicle model.

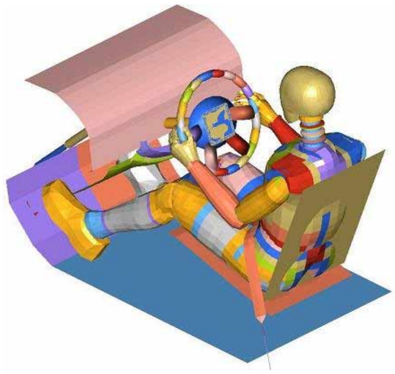

Figure 2. MADYMO occupant dummy model.

2. BASIC STUDY OF STIFFNESS MATCHING

As a first step, basic study of stiffness matching by means of simplified method was made.

When SUV with mass of m_1 and pre-impact velocity of v_1 impacts on car with mass of m_2 and pre-impact velocity of v_2, the impact phenomenon can be modeled simply as shown in Figure 3.

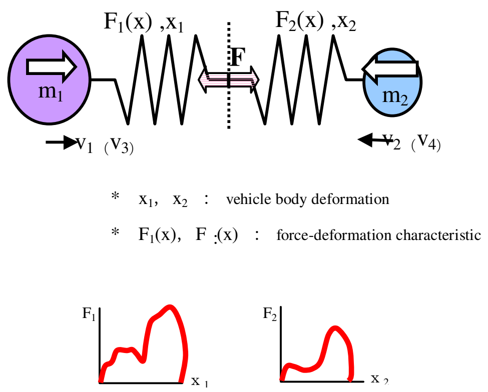

Figure 3. Simplified SUV-to-car impact model.

In this case, from the law of conservation of momentum (1) and the definition of coefficient of restitution (2), post-impact velocity of each vehicle can be described as (3) and (4).

$$m_1 v_1 + m_2 v_2 = m_1 v_3 + m_2 v_4 \qquad \cdots\cdots(1).$$

$$v_3 + v_4 = e \cdot (v_1 + v_2) \qquad \cdots\cdots(2).$$

$$\therefore$$

$$v_3 = v_1 - \frac{m_2}{(m_1 + m_2)}(1+e)\cdot(v_1 + v_2) \qquad \cdots\cdots(3).$$

$$v_4 = v_2 - \frac{m_1}{(m_1 + m_2)}(1+e)\cdot(v_1 + v_2) \qquad \cdots\cdots(4).$$

where,

m_1,m_2 : mass of vehicle

v_1,v_2 : pre-impact velocity

v_3,v_4 : post-impact velocity

e : coefficient of restitution

The energy which is spent to deform both vehicles, the deformation energy E, is given by equation (5).

$$E = \frac{1}{2}(m_1 {v_1}^2 + m_2 {v_2}^2) - \frac{1}{2}(m_1 {v_3}^2 + m_2 {v_4}^2)$$
$$= \frac{1}{2}\frac{m_1 \cdot m_2}{m_1 + m_2}(1-e^2)(v_1 + v_2)^2 \qquad \cdots\cdots(5).$$

Impact forces F acting on front of each vehicle are equal by law of action and reaction. Therefore, deformation of each vehicle x_1,x_2 in the impact are calculated under condition satisfying equation (6) on force-deformation characteristic curves F_1, F_2, as figure below.

$$\int_0^{x_1} F_1(x)dx + \int_0^{x_2} F_2(x)dx = E_1 + E_2 = E \cdots\cdots(6).$$

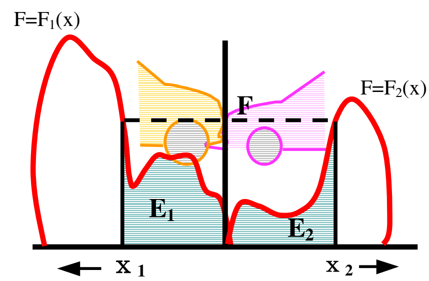

Figure 4. Calculation method of vehicle deformation.

According to the above-mentioned method, the deformation of each vehicle body in frontal SUV-to-car impact under the condition shown in Table 1 was predicted using each vehicle's force-deformation curve obtained in MADYMO 64km/h ODB impact simulation (Figure 5). From Figure 5 it is known that there is a great difference in stiffness between two vehicles. Figure 6 shows the result of predicted deformation. Here, coefficient of restitution is set at zero.

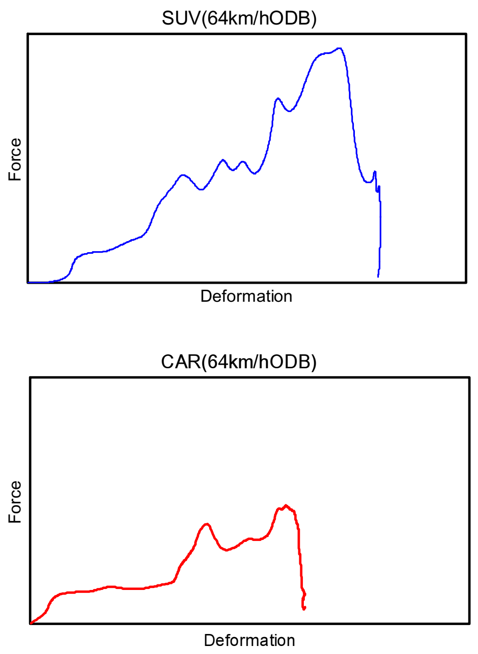

Figure 5.
Calculated force-deformation curve
(MADYMO vehicle model, 64km/h ODB condition).

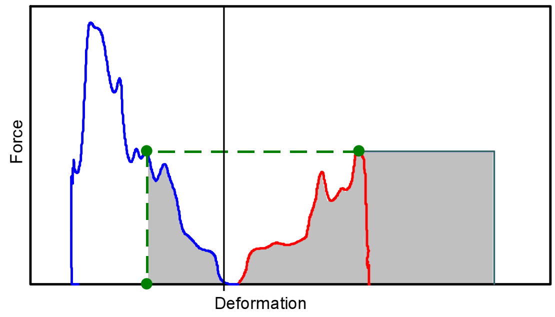

Figure 6. Predicted force-deformation curve (SUV-to-car impact).

The ceiling of impact force F is determined by the car body stiffness therefore car bears unilaterally most of impact energy. Consequently body deformation of SUV is reduced to 56% of 64km/h ODB condition, whereas that of car increases to 196%. This result is not considered compatible. The stiffness mismatch leads to this result.

In this case, there are the following approaches to reduce deformation of car body.

(a) By decreasing the stiffness of SUV, increase the deformation and impact energy absorption of SUV.

(b) By increasing the stiffness of car, increase impact energy absorption of SUV.

It is difficult to adopt approach (a), because this is directly connected to drop of self-protection performance of SUV in fixed-barrier tests. Accordingly, approach (b) is adopted and required amount of stiffness increase to reduce car body deformation is predicted (Figure 7). In this case, the target of reducing deformation as same level as that in fixed-barrier tests is set.

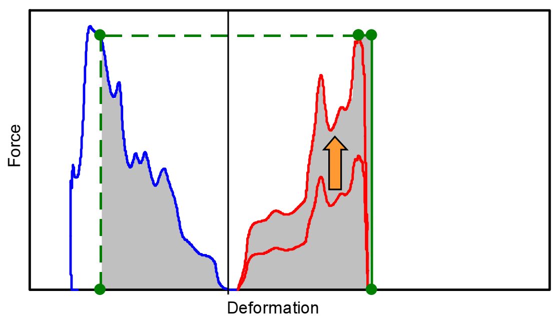

Figure 7.
Predicted force-deformation curve and required amount of stiffness increase (SUV-to-car impact).

Figure 7 shows that the car's deformation in frontal SUV-to-car impact will be comparable to that in 64km/h ODB impact by increasing car's stiffness 1.9 times throughout. This result is considered as compatible.

Here, an attempt to take vehicle stiffness apart to pieces was made. In frontal impact of a vehicle, behavior of power-train and body is quasi-independent. Consequently, it is possible to separate the reaction force of vehicle into two forces generated by each [1]. Generally, the former is called "Mechanical force", the latter "Structural force". Based on this approach, the result that force-deformation curve of the car separated into above two forces is shown in Figure 8.

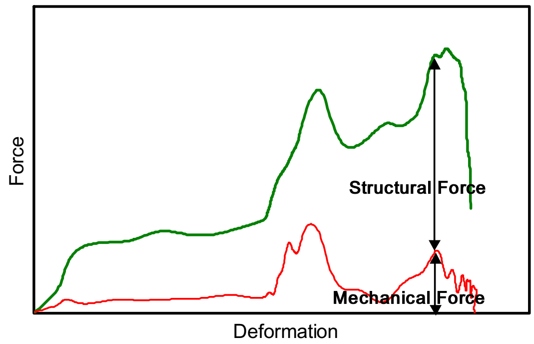

Figure 8.
Force-deformation curve of car and its component (MADYMO vehicle model, 64km/h ODB condition).

At the neighborhood of the peak, nearly 25% of car's reaction force consists of "Mechanical force" generated by inertia force of power-train. However, it is difficult to control vehicle stiffness by this component in actual car. Consequently, it is necessary to achieve target stiffness mainly by increasing "Structural force". According to this, required increase of car body stiffness is estimated as 2.2 times by equation (7).

$$\frac{Structural\quad Force(reinforced)}{Structural\quad Force(original)} = \frac{1.9-0.25}{1-0.25} = 2.2 \quad \cdots\cdots \quad (7).$$

3. DETAILED STUDY OF STIFFNESS MATCHING USING SUV-TO-CAR MADYMO MODEL

From the study using simplified method in former chapter, the possibility is shown that required increase of car body stiffness amounts to 2.2 times as much as original car to reduce car body deformation in frontal SUV-to-car impact. In this method, force-deformation characteristic of each vehicle is modeled as single spring with force-deformation curve obtained by the simulation under 64km/h ODB condition. However, because the structure of actual vehicle is more complicated, there is some possibility that those fixed force-deformation characteristics are not always appropriate.

Accordingly, as next stage, simulations in which two MADYMO vehicle models (Figure 1) collide mutually were conducted.

Figure 9 is the calculated result of frontal SUV-to-car impact simulation in which each vehicle collides mutually under the condition shown in Table 1. In case of this simulation, contact definition in MADYMO model is set so that main structural members such as side-frame of both vehicles may transmit impact force mutually and structural interaction become satisfactory. Viewing the result, it is clear that deformation of car body becomes larger than that of SUV, and an unbalance of energy absorption occurs. Body deformation of SUV is reduced to 80% of 64km/h ODB condition, whereas that of car increases up to 150%.

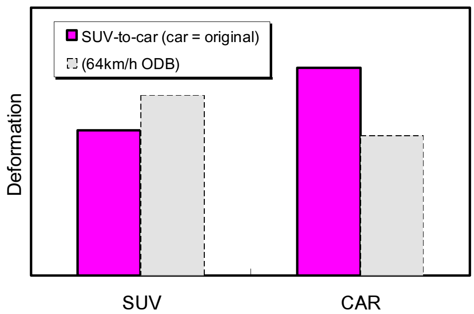

Figure 9. Calculated vehicle body deformation of MADYMO vehicle model (64km/h ODB & SUV-to-car(original) impact).

In the next step, an attempt was made to set deformation of each vehicle compatible by increasing strength of main members of car body. In case of increasing strength, each member is multiplied by its optimized ratio instead of a common ratio, so that the deceleration-deformation curve of the vehicle become close to a rectangle. By this way, occupants will be restrained in earlier stage of impact and this enables to make good use of ride-down effect, and so car body characteristic become favorable from occupant injury point of view.

Result of SUV-to-car (reinforced) impact simulation is shown in Figure 10. With the stiffness increase of car, more impact energy is absorbed by SUV that result in large reduction of car body deformation. As a result, the deformation of both SUV and car become nearly same as that of 64km/h ODB condition and the deformation of each vehicle become compatible.

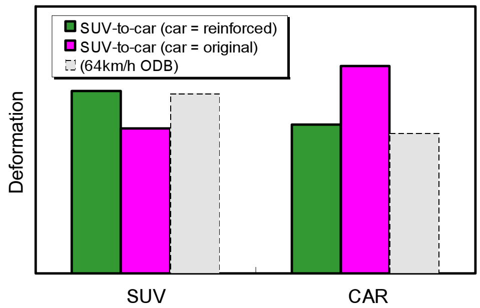

Figure 10. Calculated vehicle body deformation of MADYMO vehicle model (64km/h ODB & SUV-to-car(reinforced) impact).

In Figure 11, strength of each part of main members before/after reinforcement is shown. The ratios of strength increase vary with members and result in the range from 1.3 to 32 times.

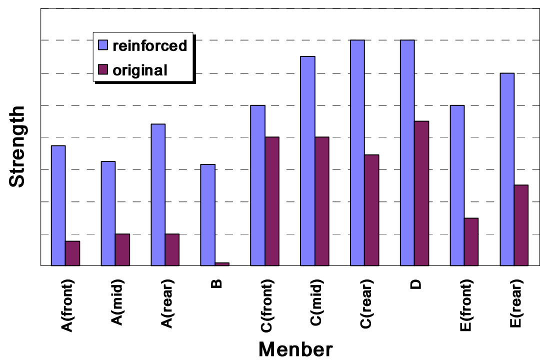

Figure 11. Strength of members of car model.

To estimate the increase of body stiffness, section force of reinforced car body was calculated, by means of adding up strength of members in above per a section crossing x-axis of vehicle. Calculated value normalized by that of original car was 2.2, in the section that affects the peak force of body.

From the study above using SUV-to-car MADYMO model, it is shown that to reduce car body deformation in frontal SUV-to-car impact, required amount of stiffness increase is over 2 times even if structural interaction is satisfactory. This corresponds closely with the result of simplified method in former chapter as a result (See Figure 7-8 and equation (7)). Each result suggests the importance of helping match stiffness in frontal SUV-to-car impact.

4. INFLUENCE OF STIFFNESS MATCHING ON FRONTAL FIXED-BARRIER IMPACT PERFORMANCE

To help keep occupant's compartment space during a frontal impact is one aspect of self-protection process. In case of frontal SUV-to-car impact, it can be achieved by limiting body deformation to an appropriate level. The most effective measure is to match stiffness of both vehicles as mentioned above.

However, once vehicle stiffness is increased, vehicle deceleration in fixed-barrier tests increases in accordance with the relation F=m*a, since mass increase due to reinforcement is generally small in comparison with stiffness increase. In this case, vehicle stops its motion within smaller displacement, and to prevent occupant from hitting cabin inner, it is necessary to strengthen power of restraint system. As a result, occupant injury indexes may become worse in fixed-barrier tests.

So in this chapter, verification of the influence arose from increase of car body stiffness to cope with frontal SUV-to-car impact on occupant injury indexes in fixed-barrier tests was conducted.

In the first place, deceleration-displacement curves of original/reinforced car calculated with MADYMO model under fixed-barrier test conditions are shown in Figure 12-13. As mentioned above, by increasing body stiffness, displacement become small and deceleration increases about 20% throughout.

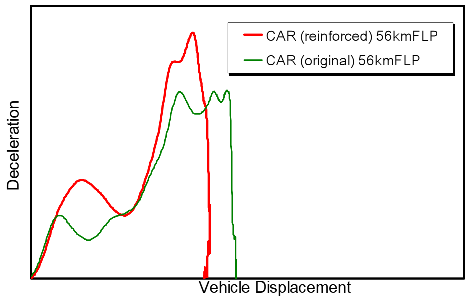

Figure 12. Deceleration-displacement curve of MADYMO vehicle model (56km/h Full-overlap).

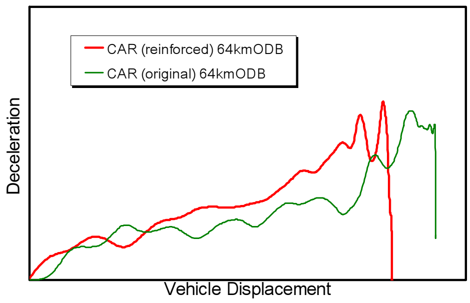

Figure 13. Deceleration-displacement curve of MADYMO vehicle model (64km/h ODB).

Occupant injury indexes were calculated under the condition shown in Table 2. Calculations were performed using MADYMO occupant dummy model (See Figure 2), for driver (AM50, belted) case only. Here, the parameters of restraint system of car (original) were set along to typical specifications of corresponding vehicle class. On the other hand, those of car (reinforced) were adjusted in a realistic range so that injury indexes might become as good as possible. In the concrete, parameters such as air-bag power, steering column absorbing load, seat belt load-limiting force were adjusted.

Table 2.
Calculation conditions of occupant injury indexes

Case	**1**	**2**	**3**	**4**
body stiffness	**Original**		**Reinforced**	
Impact condition	56km/h Full-overlap	64km/h ODB	56km/h Full-overlap	64km/h ODB
Restraint system	Typical	←	Adjusted	←

Calculated results about main injury indexes of car (reinforced) are shown in Figure 14. Values in the graph were normalized using those of car (original). Every item shown in this graph is higher when compared those of car (original). Especially, deterioration of HIC and chest-G is large, and those become 1.85 and 1.36 times each in comparison with that of car (original). Despite adjusting restraint system as much as possible, deterioration of occupant injury indexes was unavoidable as a result.

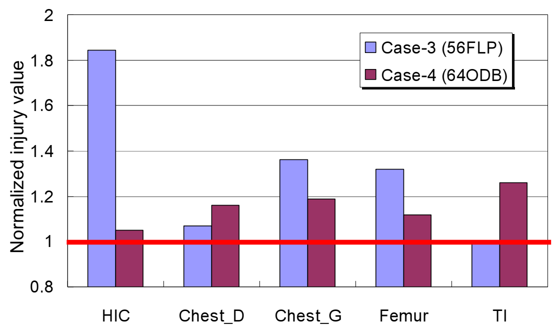

Figure 14.
Normalized injury indexes of occupant dummy.

5. DISCUSSION

The study above shows for the scenarios analyzed that in order to realize good impact compatibility from the viewpoint of stiffness-matching, it would be necessary to increase body stiffness of the car over two times.

It is very difficult to increase body stiffness within realistic mass rise that affects little on fundamental performance of vehicle. Moreover, even if it can be realized, it becomes clear that such body reinforcement increases deceleration of vehicle in fixed-barrier impact tests, and this led to deterioration of occupant injury indexes.

These facts indicates that it is very difficult to cope with both measures to accomplish good impact compatibility in frontal SUV-to-car impact and measures to accomplish sufficiently low occupant injury indexes in fixed-barrier tests.

Since design and evaluation methods for self-protection performance are based on government mandated and to some extent market driven fixed barrier impact tests that consequently require a vehicle stiffness strongly related to mass, it is difficult to simultaneously achieve enhanced compatibility. However, from a purely frontal impact compatibility point of view, it is necessary to harmonize frontal stiffness of vehicles by means of increasing the stiffness of lighter vehicle or decreasing that of heavier vehicle. In efforts to accomplish the enhanced compatibility, it is desirable that such changes to vehicle stiffness will not reduce the self-protection performance.

In order to enhance compatibility while still maintaining self protection performance, harmonizing the use of MDB to imitate vehicle stiffness with government mandated self protection performance test procedures appears to be needed. However, in order to actualize the above, further studies are required about specification of MDB that has meaning as vehicle stiffness standard, and evaluation method for partner protection performance (including structural interaction which is set forth as a prerequisite in this paper).

In this paper, influences by the increase of body stiffness so as to achieve frontal compatibility on other impact modes (i.e. a stiffer car could be impacting the sides of other vehicles) and influences by mass-ratio of each vehicle on deceleration characteristic of smaller vehicle, were not considered. However, these are important matters in an attempt to achieve improved compatibility, and so further research may be needed.

6. CONCLUSIONS

Taking up full-sized SUV and middle-sized sedan, an attempt to quantitatively evaluate the matters mentioned below on 56km/h frontal offset SUV-to-car impact condition was made.

i) Required the increase of the car body stiffness to lower the deformation of car body.

ii) Influence of the increase of car body stiffness on occupant injury indexes in fixed-barrier impact tests.

As a result, following knowledge was obtained.

i) In order to limit deformation of car body as same level as that in fixed-barrier tests, even if structural interaction is satisfactory, stiffness of car body must be increased up to double, based on the models used for this research.

ii) In case of above realized, even if occupant restraint system is adjusted using currently available technology among current vehicles, occupant injury indexes in fixed-barrier impact tests deteriorate in this study.

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VEHICLE MASS, STIFFNESS AND THEIR RELATIONSHIP

Guy S. Nusholtz
Lan Xu
Yibing Shi
Laura Di Domenico
DaimlerChrysler Corporation
United States

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ABSTRACT

Vehicle stiffness is a commonly used parameter in the field of vehicle safety. But a single-valued "stiffness", although well defined for the linear case, is not well defined for non-linear systems, such as vehicle crashes. Moreover, the relationship between vehicle stiffness and mass remains confusing. One previous work [1] addresses this issue. Multiple definitions of stiffness were used to address the lack of a clear definition of stiffness. The R^2 values for the correlation between mass and each stiffness measure were presented. The results showed that no clear relationship existed between mass and any of the stiffness measures. The results from a statistical analysis indicated that there were differences in stiffness between different types of vehicles.

This paper extends the same research by including a significant amount of new data samples as well as some different analysis procedures. Results show that mass is poorly correlated to stiffness and for some vehicle types mass correlates better to vehicle crush than to stiffness. In addition, it is shown that even without a well-defined definition of stiffness different levels of stiffness can be defined and differences in stiffness between different vehicle types can be quantitatively and qualitatively established.

INTRODUCTION

The most influential vehicle parameters in frontal crash and compatibility are the mass [2, 3, 4], the stiffness as well as the geometry; the latter two are not well understood and appear to be less significant. The relationship between mass and stiffness (a single-valued parameter) has been a subject of study for some time. One proposition [5] is that the mass ratio of two colliding vehicles has historically been incorrectly identified as the cause of compatibility problems because stiffness is the actual parameter at play, except it is not available in accidents statistics, but it is related to mass. However, stiffness, which is a description of the crash response, is a complicated concept, and warrants a systematic discussion.

The crash response of each vehicle, used to derive stiffness, depends on its detailed force displacement history. A complete characterization would involve details at the micro level. While this is necessary for an individual vehicle analysis, it results in a computationally intractable problem when general analysis across a vehicle fleet is needed. A characterization at a higher level is more appropriate. One such characterization of the crash response is to use barrier (rigid or deformable) test data. Indeed, this approach has been used lately in several studies [6, 7]. The term "stiffness", without being clearly defined, has been used loosely as a measure that describes the force-crush behavior. This has resulted in some difficulty, confusion and misinterpretation of results and conclusions.

A recent study [1] attempted to address the topic of stiffness and its relationship with mass. Vehicle stiffness, either static or dynamic, is a vague concept. It has precise meaning only in linear elastic deformation which is not the case in a vehicle crash. In an attempt to address the lack of a well-formed stiffness definition, multiple stiffness definitions were used in that study [1]. The use of several physically meaningful stiffness measures allows a relationship between mass and stiffness to be studied without having to have one specific stiffness definition. This assumes that there are enough stiffness measures that are different enough and they span the space of "reasonable" stiffness definitions; therefore, if there is a relationship between mass and stiffness for the majority of these stiffness definitions, then there is a relationship between mass and stiffness in general.

Eight different stiffness measures were defined in the previous study [1]. Then the mass-stiffness correlation analysis and stiffness characteristic study among different type of vehicles were performed by using the NHTSA NCAP tests, mostly from model year 1999 to 2003. It was conclude that only a weak relationship between mass and stiffness appeared to exist. The stiffness of different vehicle types and their relative ranking system were found to depend on the definition of the stiffness.

The objective of this study is to advance the previous study by including a larger sample size with a more extensive model year coverage. The previous study included 175 vehicles from 1999 to 2003, while the current study includes 585 vehicles and spans the model years 1979-2004. The analysis procedures used in the previous study are followed here. The only difference is the addition of a new parameter, the maximum crush, and its relationship with mass.

METHODOLOGY

The NCAP test data used in this paper were obtained from NHTSA database for the model years 1979 to 2004. The vehicles were grouped into four different types, Car, Van, SUV, and Truck, according to the U.S. Environmental Protection Agency (EPA) classifications. Among the vehicles used, about 66% were Cars, 14% were SUVs, 11% were Trucks, and 9% were Vans.

Based on barrier force and vehicle displacement, 4 different definitions of stiffness for a total of 9 measures were considered. Test data were excluded from the analysis if the linear impulse and momentum were not consistent (the integral of force-time was not close to the vehicle momentum), load cell or accelerometer data were missing, or there was instrumentation errors. The SAE CFC60 filter was used to filter the barrier forces.

Essentially two statistical analyses were performed: a linear regression analysis, and a multiple comparison analysis. The linear regression was applied to study the correlation of vehicle mass and various stiffness measures. The coefficient of linear determination, R^2, has been used to describe the degree of linear association [8].

The next step was to perform a multiple comparison analysis of vehicle-type stiffness values by means of the Tukey procedure [8], using a family confidence coefficient of 90%. The family confidence coefficient pertaining to the multiple pairwise comparisons refers to the proportions of correct families, each consisting of all pairwise comparisons, when repeated sets of samples are selected and all pairwise confidence intervals are calculated each time. A family of pairwise comparisons is considered to be correct if every pairwise comparison in the family is correct. Thus, a family confidence coefficient of 90% indicates that all pairwise comparisons in the family will be correct in 90 percent of the repetitions.

STIFFNESS DEFINITIONS

Definition 1: "Linear" Stiffness

For a given barrier force versus vehicle displacement curve F(d), a line is obtained by a least square fit over a given displacement range. The slope of this line is defined as the "linear" stiffness over the displacement range considered. Two "linear" stiffness measures were used in this paper, depending on the range of the displacement considered. The first, noted as K1, has a displacement range from 25 to 250 mm, as shown in Figure 1. The second, K2, has a displacement range from 25 to 400 mm.

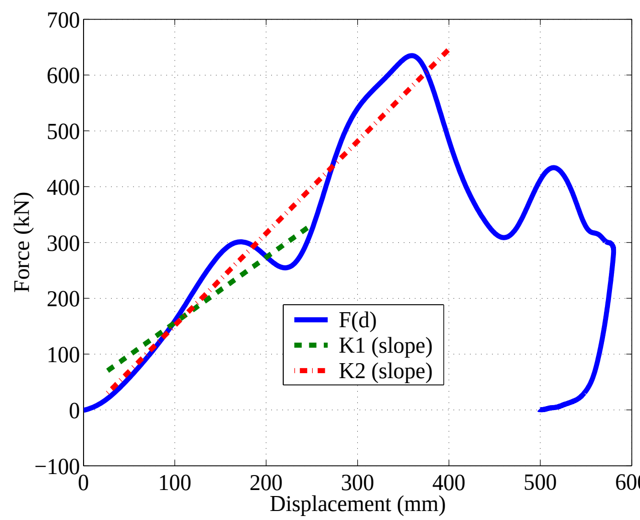

Figure 1. Illustration of "Linear" Stiffness (K1 and K2)

Definition 2: Energy-Equivalent Stiffness

The energy-equivalent stiffness (Ke) is defined as Ke=F*2/d, where F is the average force over the displacement range [25 mm, d]. Two energy-equivalent stiffness measures were used, one with d equal to 250 mm, and the other with d equal to 400 mm, i.e., Ke1=F1*2/(250-25) (unit: force/mm) and Ke2=F2*2/(400-25) (unit: force/mm), as shown in Figure 2.

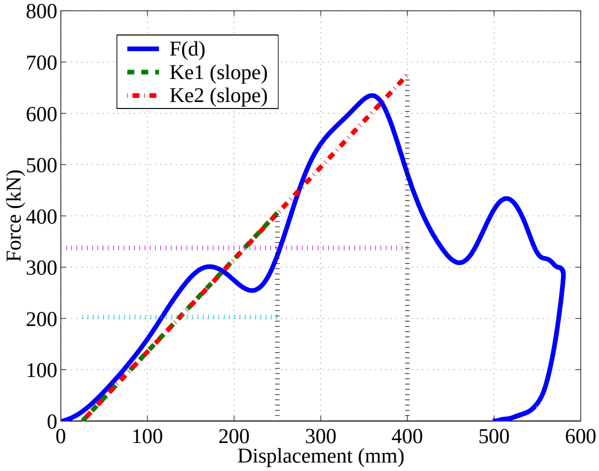

Figure 2. Illustration of Energy-Equivalent Stiffness (Ke1 and Ke2)

Definition 3: Global Linear Energy-Equivalent Stiffness

The global linear energy-equivalent stiffness is defined as $Ke3=M*V^2/Xm^2$, where M is the vehicle mass, V is impact speed and Xm is the maximum displacement of the vehicle. This is obtained by an approximation of the conservation of total energy and by assuming the force is F=Ke3*d, where Ke3 is a stiffness and d is the vehicle displacement.

Definition 4: Peak Force as a Stiffness Metric

In addition to the three stiffness definitions above, three peak barrier forces were also used. It is recognized that the use of the peak force is the least representative of the stiffness. They are defined as following:

Fp1 = max (F(d)), 25 mm<d<250 mm;
Fp2 = max (F(d)), 25 mm<d<400 mm;
Fp = max (F(d)), 25 mm<d<Xm,
where Xm is the maximum displacement.

RESULTS AND OBSERVATIONS

Linear Regression Procedure

The R^2 values which describe the degree of linear association between mass and the various stiffness measures are presented in Table1. The results for five different vehicle groups are listed in the Table. The first group in row two includes all the vehicles, and the other four are subgroups of different vehicle types.

Table 1. Mass-Stiffness R^2 Value (1979-2004)

	K1	Ke1	K2	Ke2	Ke3	Fp1	Fp2	Fp
All	0.27	0.24	0.11	0.28	0.35	0.32	0.19	0.48
Car	0.02	0.02	0.08	0.08	0.13	0.04	0.09	0.37
SUV	0.05	0.03	0.00	0.02	0.00	0.03	0.00	0.13
Truck	0.02	0.05	0.02	0.01	0.01	0.02	0.02	0.06
Van	0.13	0.06	0.10	0.10	0.12	0.12	0.10	0.36

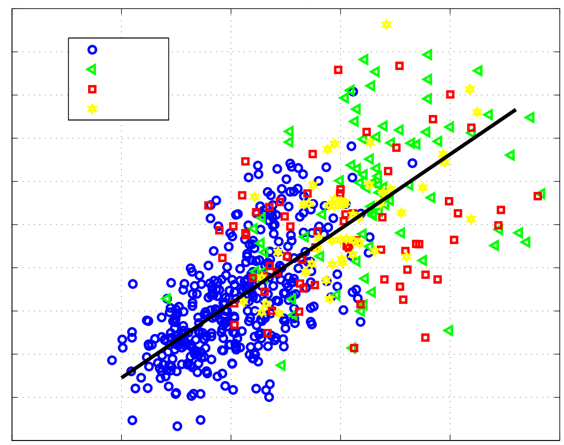

Figure 3. Mass and Peak Force

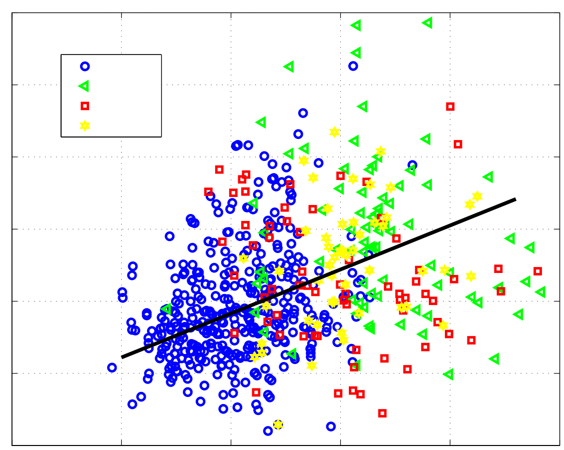

Figure 4. Mass and Stiffness Measure K2

Many values in Table 1 are close to zero with the highest value below 0.5, which indicates a very weak correlation between the two. The highest correlation exists between mass and peak force, with the R^2 value of 0.48, for the all vehicle group, as shown in Figure 3. The lowest correlation exists between mass and K2 with the R^2 value of 0.11, for the all vehicle group, which is shown in Figure 4. Moreover, the correlation, for most stiffness measures, in the all vehicle group is, in general, higher than that for each individual subgroup.

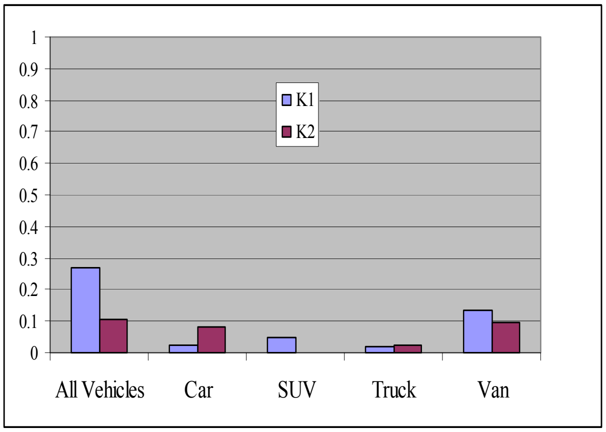

Figure 5. R^2 Values of Mass and "Linear" Stiffness

The results for the R^2 values between the two "linear" stiffness measures K1 or K2 and mass are shown in Figure 5. In general, there is very weak correlation between mass and either K1 or K2 for the subgroups.

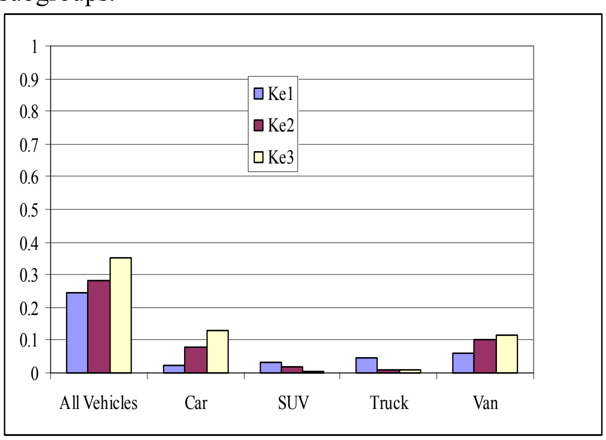

Figure 6. R^2 Values of Mass and Energy-Equivalent Stiffness

The results for the R^2 values between the three energy-equivalent stiffness measures, Ke1, Ke2, and Ke3 and mass are shown in Figure 6. All the values are below 0.35. It seems that there is almost no correlation between mass and any of these three stiffness measures for the SUV and Truck subgroups.

In general, Ke3 has a relatively higher correlation with mass, while Ke1 has a relatively lower correlation with mass for the Car and Van subgroups, even though the correlations are weak.

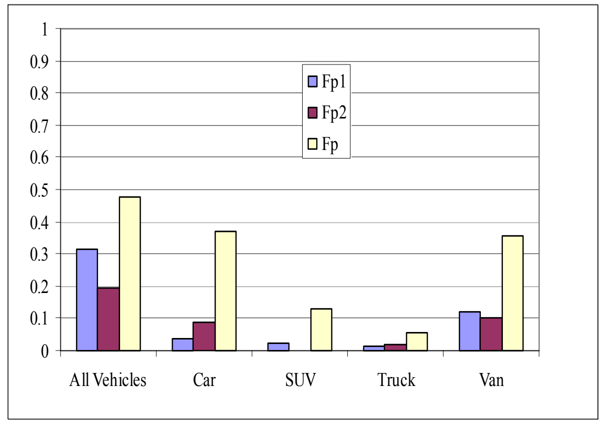

Figure 7. R^2 Values of Mass and Peak Barrier Force

The results for the R^2 values between peak forces and mass are shown in Figure 7. In general, Fp shows a relatively higher correlation across all the groups, especially for the Car and Van subgroups.

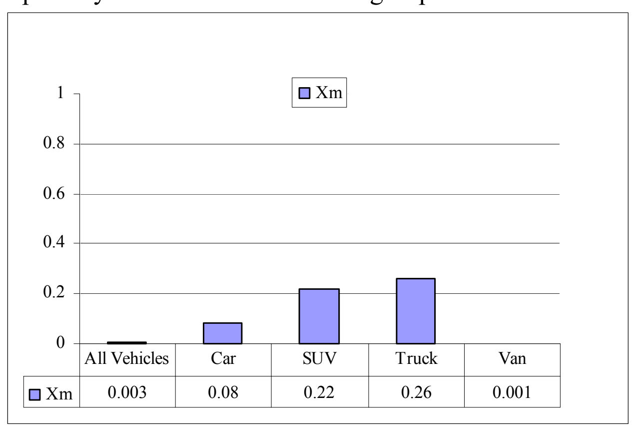

Figure 8. R^2 Values of Mass and Maximum Crush Xm

The maximum crush Xm, is the maximum vehicle displacement over the duration of the vehicle crash, obtained from double integration of the vehicle acceleration with the initial velocity of 35mph. The results for the R^2 values between Xm and mass are shown in Figure 8. In general, the lowest correlation between mass and Xm is for the Van subgroup and the all vehicle group with the highest correlations for the Truck and SUV subgroups.

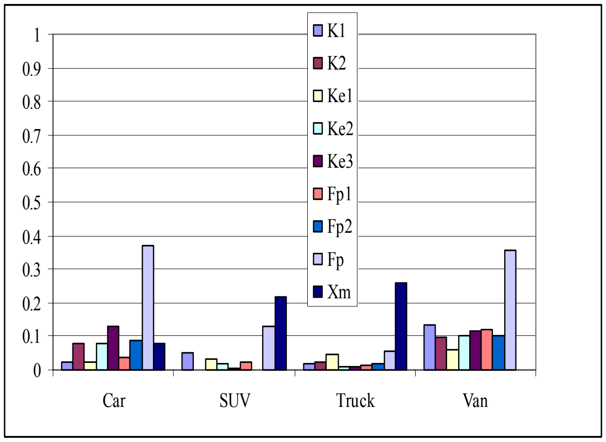

Figure 9. R^2 Values of Mass and All Stiffness Measures for the Subgroups

The results for the R^2 values between mass and all the stiffness measures, as well as mass and maximum crush for all the subgroups are shown in Figure 9. Either peak force Fp or maximum crush Xm has the highest correlation with mass. For Car and Van subgroups, peak force correlates the strongest with mass, while maximum crush Xm correlates with mass the strongest for the SUV and Truck subgroups.

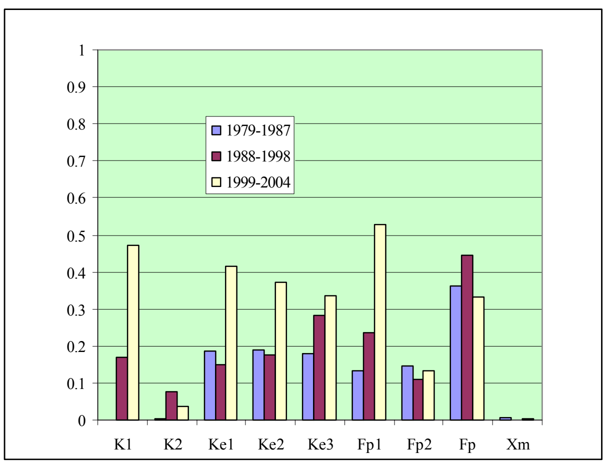

Figure 10. R^2 Values of Mass and all the Stiffness Measures for All Vehicle Group at Different Time Period

The results for the R^2 values between all the stiffness measures and mass at different time periods are shown in Figure 10. The whole time period from 1979 to 2004 is divided into three sub periods: from 1979 to 1987, from 1988 to 1989, and the last one from 1999 to 2004. It is observed from Figure 10 that peak forces Fp and Fp2 show the most consistent correlations with the mass across the different time periods. The correlation changes significantly between either K1 or Fp1 and mass, among these three different time periods. The correlations between average forces (Ke1 and Ke2) and mass change little from the period 1979-1987 to period1988-1998. But, they change significantly from period 1988-1998 to period 1999-2004.

Multiple Comparisons Procedure

The data used for the comparison are 1979 to 2004 model year NCAP tests. The results of the multiple comparisons procedure are shown in Figures 11-15. The absence of a solid line between two different vehicle types implies that a difference in stiffness has been found. The location of mean stiffness values, (the whisker-points in the upper half of the figure), indicates the direction of the difference. On the other hand, the presence of a solid line between two vehicle types indicates that the two vehicle types have statistically similar stiffness values.

For example, in Figure 11, the continuous solid lines between circles, squares, and diamonds, starting from Van type and passing Truck type and ending at SUV type, indicate that there are no substantial stiffness differences among these three vehicle types, by using Ke1, or Ke2, or Ke3. However, the absence of a solid line between Car type and any of the other types shows that Cars are different from all other type of vehicles.

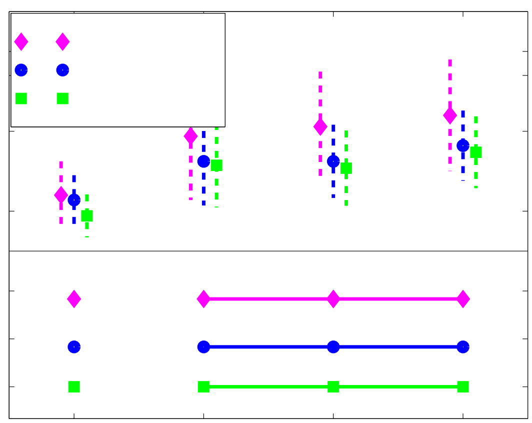

Figure 11. Ke1, Ke2 and Ke3 Stiffness Results. The Dashed Lines Indicate One Standard Deviation from The Mean Values. Each Non-Significant Difference between Two Vehicle Types Is Indicated by a Solid Line.

Thus, the multiple comparison procedure for Ke1, Ke2 and Ke3 lead to infer, with a 90% family confidence coefficient, that essentially there are only two different stiffness groups: a less stiff Car group and a significantly stiffer group that includes Vans, Trucks and SUVs.

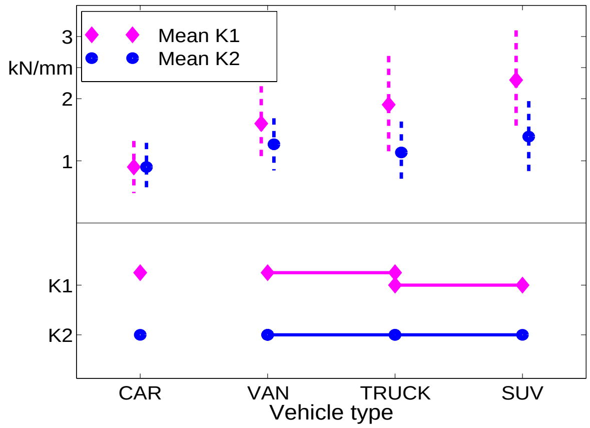

Figure 12. K1 and K2 Stiffness Results. The Dashed Lines Indicate One Standard Deviation from The Mean Values. Each Non-Significant Difference between Two Vehicle Types Is Indicated by a Solid Line.

The results from the stiffness measures Ke1, Ke2 and Ke3 are considered to be more informative than the ones from K1 and K2, since Ke1, Ke2 and Ke3 are based on energy relationship, while K1 and K2 have neither a momentum nor an energy relationship foundation. However, for completeness the results using K1 and K2 are also presented (see Figure 12). From the stiffness measures K1 and K2, it is possible to draw conclusions similar to the ones deduced using Ke1, Ke2, and Ke3. There is still evidence of only two different stiffness groups: a Car type less stiff group and a SUV type stiffer group. In particular, using K2, the same conclusion is reached by using Ke1, Ke2, and Ke3. While, using K1, the figure indicates that the Van and Truck groups show the similar stiffness value and the Truck and the SUV are similar too. But the SUV type is significantly stiffer than the Van type. One might see it as a contradiction; however, there is no contradiction, because the statistically similar property is not transitive.

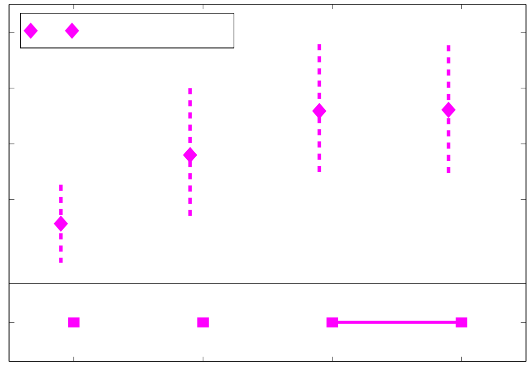

Figure 13. Peak Force Fp1 Results. The Dashed Lines Indicate One Standard Deviation from The Mean Value. Each Non-Significant Difference between Two Vehicle Types Is Indicated by a Solid Line.

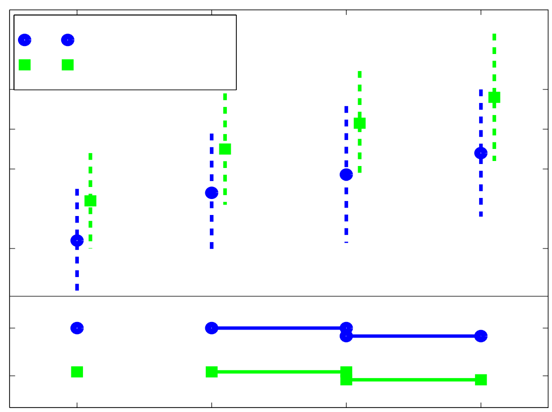

Figure 14. Peak Force Fp2 and Fp Results. The Dashed Lines Indicate One Standard Deviation from The Mean Value. Each Non-Significant Difference between Two Vehicle Types Is Indicated by a Solid Line.

The results for the three measures of peak barrier forces considered (Fp1, Fp2 and Fp) are presented in Figure 13 and 14. Figure 13 shows that, within the first 250 mm range (i.e., Fp1), the peak force Fp1 for the Truck type and SUV type is similar. But, there is substantial peak barrier force difference between the Cars and the Vans, and between the Vans and the Trucks. The peak barrier force for the Cars is substantially smaller than that for the Vans; and the peak force for the Vans is also substantially smaller than for the Trucks and SUVs. The results are different when the range is extended to 400 mm or further (i.e., Fp2 and Fp in Figure 14). In this case the peak barrier force value for the Car type is clearly the smallest. The SUVs and the Vans are similar, the Trucks and the Vans are similar, but the Trucks and the SUVs are not.

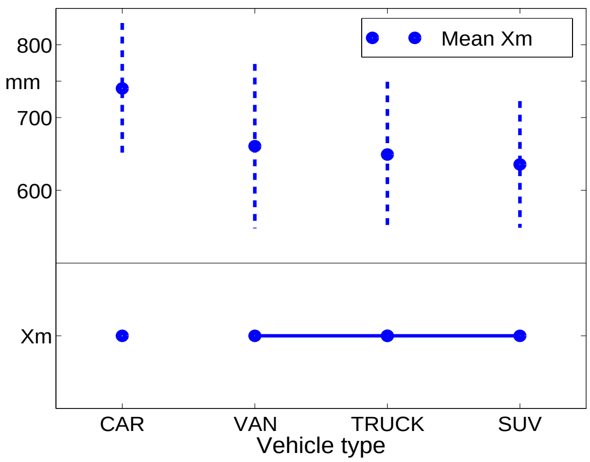

Figure 15. Maximum Crush Results. The Dashed Lines Indicate One Standard Deviation from The Mean Value. Each Non-Significant Difference between Two Vehicle Types Is Indicated by a Solid Line.

The results of maximum vehicle crush Xm are presented in Figure 15. Statistically there are only two groups. One is the Car group which has the largest maximum crush and the other group includes the Vans, Trucks and SUVs, which shows less maximum crush.

DISCUSSION

In this study NHTSA NCAP test data have been used to investigate the relationship between mass and stiffness. The primary reasons to use the NCAP tests are that there are enough samples to obtain reliable statistical analyses; the experimental procedures are robust and repeatable; and there is enough instrumentation for the analysis. In addition, there is significant crush of the vehicle front. These tests also approximate head-on crashes in the field. Nonetheless, by using multiple definitions of stiffness, the results should be more general than if only one definition was used. However, there are some limitations with using the NCAP data. Most notably, the stiffness measures derived with such data may not be directly useful for other modes of crashes.

Compared to the previous study [1], no significant changes have been observed in the relationships between mass and stiffness. But, there are some changes of the stiffness magnitudes and relative stiffness ranking among different vehicle types.

The sample size used in this paper is different from that in [1]. The sample size has been enlarged from model year 1999-2003 to model year 1979-2004. The number of samples were increased from 175 to 585. The distribution of different types of vehicles has been changed. The percentage of Cars increased from 55% to 66% and a higher percentage of large Cars (mass 1900kg and up) was included. The percentage of Vans and Trucks increased slightly. But the percentage of heavy (full sized) Vans has increased along with the percentage of light trucks. The percentage of SUV decreased significantly, from 25% to 14%, due to the fact that there were very few SUVs before the model year 1993.

It is observed that the correlation between mass and various stiffness measures has not changed significantly: Comparing Table 1 and Table 2 (from [1]), all the correlations are weak. The correlation for most of the stiffness measures, in the all-vehicle group is in general higher than for each individual subgroup. The R^2 values for K1, and K2, are lower with the larger sample size. Comparing the mass correlation with Ke1, Ke2, and Ke3, the R^2 value for the Ke1 is the highest and Ke3 is the lowest for the all vehicle group in previous study, but the trends are reversed in this study. Ke1 and Ke2 had a relatively high correlation with mass for the SUV and Truck subgroups in previous study, but it is not observed in this study. Due to a graphing error in [1] it is not possible to compare the peak forces from the previous study with those in the current study.

Table 2. Mass-Stiffness R^2 Value (1999 to 2003)

	K1	Ke1	K2	Ke2	Ke3	Fp1	Fp2	Fp
All	0.43	0.46	0.02	0.41	0.28	0.49	0.16	0.32
Car	0.04	0.08	0.07	0.14	0.09	0.07	0.12	0.27
SUV	0.31	0.28	0.09	0.07	0.01	0.18	0.00	0.03
Truck	0.23	0.39	0.03	0.25	0.02	0.33	0.04	0.05
Van	0.32	0.27	0.31	0.28	0.09	0.25	0.38	0.34

The stiffness relationships are slightly different from the previous study .For example, the Cars have no relationships to the other three vehicle groups in this study; however, in the previous study [1] the Vans sometimes are similar to the Cars (Ke1, and Ke3), and sometimes similar to the Trucks and SUVs. This could be due to the addition of the heavy Vans (full size). For K1, the Trucks and the SUVs have similar stiffness in both studies, but the Vans are dissimilar to SUVs, which is different from the previous study [1]. For K2, the Vans and the SUVs have the similar stiffness in both studies, but the Trucks are similar to the Cars, which is different from this study.

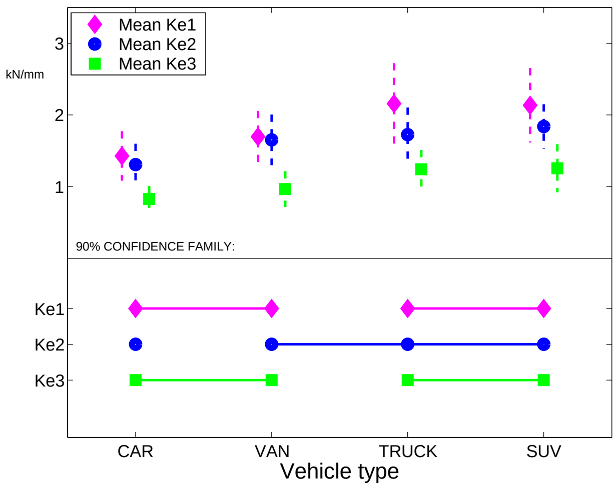

Figure 16. Ke1, Ke2 and Ke3 Stiffness Results for 1999 to 2003 MY. The Dashed Lines Indicate One Standard Deviation from The Mean Values. Each Non-Significant Difference between Two Vehicle Types Is Indicated by a Solid Line.

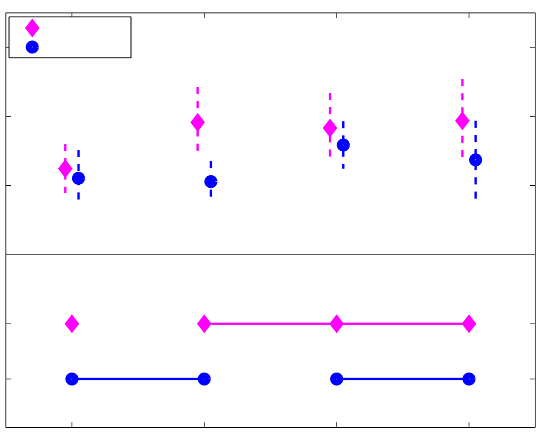

Figure 17. K1 and K2 Stiffness Results For 1999 to 2003 MY. The Dashed Lines Indicate One Standard Deviation from The Mean Values. Each Non-Significant Difference between Two Vehicle Types Is Indicated by a Solid Line.

The correlation analysis shows that there is no significant linear correlation between the different stiffness measures considered and the vehicle mass. To each vehicle type, a significant relationship between mass and stiffness does not exist. Moreover, it is also noticed that for the overall vehicle population when such a relationship exists, it is weak. The reason could be with the enlargement of the range of mass values. Though a large number of samples have been added to this study, the mass ratio has not changed significantly. Therefore, no significant change in mass-stiffness relationship has been seen in this study. However, it is clear that as the mass range increases the relationship between mass and stiffness also increases: compare the all vehicle group to any of the subgroup.

There are two parameters that correlate with the mass Best: For the Truck and SUV groups, the maximum crush Xm correlates with mass the best, while the initial peak force Fp1 correlates with mass the best for the Car and Van groups. This may be because of the structure of the vehicles.

The correlation of mass and some of the stiffness measures shows significant differences for the vehicles manufactured in different time periods: vehicle stiffness relationship with mass are time period dependent.. These may result from the regulations on passive restraint requirements and/or the Corporate Average Fuel Economy. Future regulations may also force a change in the trend of the relationship between mass and stiffness.

Since there was no clear indication of any trend between the stiffness measures and vehicle type, it was decided to estimate all pairwise comparisons. This statistical analysis gives evidence (at level alpha 0.9) that essentially there are only two different stiffness groups: a Car-type group and a stiffer Truck/SUV type group. However, for all but one definition of stiffness the Van and Truck types could be considered to have the same stiffness as the SUV type. The Cars appear to be in the lowest stiffness group with the SUV/Trucks as the highest stiffness group and the Vans close to the SUV and Truck group. However, this may be the result of including full size vans in the Van group. Minivans by themselves may have a different stiffness than SUV and Trucks.

The finding that the strong stiffness and mass in general do not have a good correlation has implications to a number of aspects for the crash safety field. One example is given here. Vehicle Mass stiffness, and geometry are often included as independent parameters in regression models [2, 3].

The correlation between these parameters, especially that between stiffness and mass has always been an issue of concern [5]. This is because the quality of the regression model (and therefore that of the risk prediction), which depends on the statistical sampling-related uncertainty of the regression coefficients, depends on the extent of the correlation between the independent parameters. This is demonstrated in Figure 18 through both theoretical prediction and a statistical simulation (Monte Carlo) for a linear regression with two independent parameters.

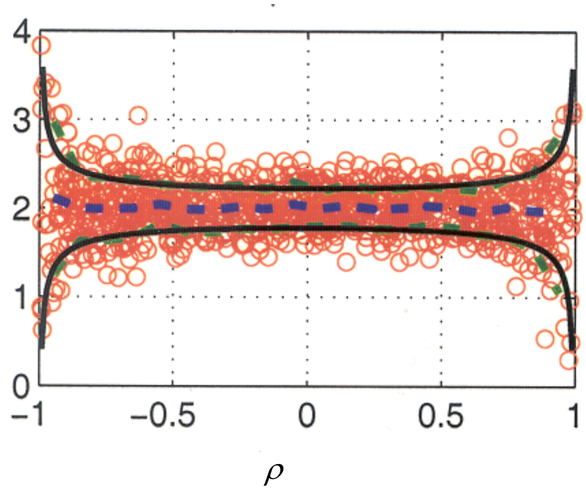

Figure 18. Theoretical prediction and Monte Carlo simulation of the dependence of variability of one of the two regression coefficients of a 2-independent variable linear regression on the extent of correlation between the independent variables. The abscissa is the coefficient of correlation, and the ordinate is the value of the coefficient estimate (The actual value of the coefficient is 2 units. The two continuous lines are theoretical prediction of the standard deviation of the estimate and each red dot is result from one of 1000 Monte Carlo regression simulations. The dashed line in the middle is the mean of the statistical simulation. The theoretical model and simulations use 2 units as the standard deviation of the independent variable; and 2 for the random sampling noise.)

Figure 18 shows that only when the Pearson's coefficient of correlation (equaling the square-root of the R^2 value in the case of two variables) is less than 0.8 (R^2 of 0.64), does the variance of the estimated coefficients stay small enough for the regression model to be useful (in theory, the variance is proportional to $1/\sqrt{1-\rho^2}$, where ρ is the coefficient of correlation). Because of the close resemblance in the underlying structure of the models this applies to both linear regression and the logistical regression. With this basic statistical observation, the finding of the current study that the stiffness and mass in general have R^2 values below 0.5 (ρ values less than 0.7) provides a basis for establishing and applying risk models based on regression involving stiffness and mass as independent variables.

CONCLUSIONS

This study employs all the available/reliable NCAP data from model years 1979 to 2004 and represents a reasonable estimate of the current fleet. The trends may change if the fleet changes significantly. But from this study, using 4 different definitions of stiffness for a total of 9 different measures, it is concluded that:

- There is no significant correlation between mass and stiffness for the vehicles in the current fleet.
- In general, for most of the stiffness definitions considered, the correlation for all vehicles together is higher than those for any of the vehicle subgroups. The qualitative relationship between stiffness and mass is theoretically sound for a large vehicle mass range (mass ratio). As the mass ratio increases the correlation increases. However, the current fleet does not have a significant mass ratio for the mass to be significantly correlated with stiffness.
- The relationship between mass and stiffness is not significant enough to contaminate any reasonable risk analysis using crash data.
- The mass correlates with the maximum crush better than stiffness for the SUV and Truck groups,
- From the definitions of stiffness used in this study, it is reasonable to assume that Cars and SUV/Trucks have different stiffness, with SUV/Trucks significantly stiffer than Cars. Vans (including full size vans are

closer to SUV/Trucks, but may not be if only minivans are included

- The correlations between mass and some stiffness measures may vary for different time periods.

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